THE IMPACT OF MENTAL FATIGUE ON PHYSIOLOGICAL, PSYCHOLOGICAL AND PERFORMANCE VARIABLES DURING EXERCISE

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Abstract

Mental fatigue is a change in psychobiological state caused by prolonged periods of demanding cognitive activity. Although mental fatigue is a common and everyday occurrence, the literature surrounding mental fatigue is almost exclusively limited to its effects on cognitive performance and attention (Lorist 2000, van der Linden, Frese et al. 2003, Boksem, Meijman et al. 2005, van der Linden and Eling 2006, Lorist 2008). In 2009, Samuele Marcora and colleagues published findings suggesting that the effect of mental fatigue extends beyond the impact on cognitive functioning, and impairs the subsequent performance of physical exercise (Marcora, Staiano et al. 2009). The aim of this thesis was therefore to expand on this initial research and further investigate the effect of mental fatigue on physiological, psychological and performance variables during exercise, as well as any possible mechanisms behind the effect. Mental fatigue was experimentally induced and its effect on maximal anaerobic exercise tasks, professional and recreational athletes, and subjects who participated in varying levels of self-regulatory lifestyle behaviours was observed.

From these studies, it was determined that maximal anaerobic exercise tasks are largely unaffected by mental fatigue. This finding contrasts the negative effect of mental fatigue on prolonged and submaximal intensity exercise performance. Time trial performance of professional road cyclists was also unaffected by prior mental exertion, whereas recreational cyclists performed worse following mental exertion compared to a control, recording a lower power output and slower average speed. Professional cyclists performed better than recreational cyclists on a mentally fatiguing cognitive task of self-regulation. Following on from this finding, regular performance of self-regulatory lifestyle behaviours including occupational cognitive demand and physical training load were associated with better maintenance of endurance performance with mental fatigue. The findings of the previous three studies, as well as findings from mental fatigue research completed concurrently were then collated to propose a physiological mechanism for the increase in rating of perceived exertion and

impaired endurance performance of mentally fatigued participants. This review also sought to explain the apparent increased resistance to mental fatigue of the professional road cyclists.

This body of research highlights the individuality of the impact of mental fatigue on physical performance, offers potential protective factors against performance decrements with mental fatigue and proposes a possible physiological mechanism for this effect. This work should be used as a basis for future research investigating the mechanism behind the negative effect of mental fatigue on endurance performance, focusing on neurochemical changes within the brain. Future research may also focus on the efficacy of a training intervention using tasks requiring self-regulation to increase tolerance for those susceptible to performance decrements with mental fatigue.

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List of Publications

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1. **Martin, K.,** Thompson, K. G., Keegan, R., Ball, N. & Rattray, B. (2015). Mental fatigue does not affect maximal anaerobic exercise performance. European Journal of Applied Physiology, 115(4), 715-725.
2. **Martin, K.,** Staiano, W., Menaspa, P., Keegan, R., Hennessey, T., Marcora, S., Martin, D., Halson, S., Thompson, K. & Rattray, B. (2016). Superior inhibitory control and resistance to mental fatigue in professional road cyclists. PloS One, 11(7), e0159907.
3. **Martin, K.,** Keegan, R., Thompson, K. G. & Rattray, B. (2017). Self-regulatory behaviours predict inhibitory control and maintenance of endurance performance with mental fatigue. (In review)
4. **Martin, K.,** Meeusen, R., Thompson, K. G., Keegan, R. & Rattray, B. (2017). Mental fatigue impairs endurance performance: A physiological explanation. (In review)

Conference Communications during the Course of this Investigation

1. **Martin, K.,** Thompson, K. G., Keegan, R., Ball, N., & Rattray, B. (2014). Mental fatigue does not affect subsequent short-term exercise performance. 6th Annual Exercise and Sports Science Australia Conference, April 10-12, Adelaide, Australia, (Poster).
2. **Martin, K.,** Staiano, W., Menaspa, P., Keegan, R., Hennessey, T., Marcora, S., Martin, D., Halson, S., Thompson, K. G. & Rattray, B. (2015). Acute mental exertion does not affect time trial performance in elite road cyclists. 20th Annual European College of Sport Science Conference. June 24-27, Malmo, Sweden, (Oral).
3. **Martin, K.,** Staiano, W., Menaspa, P., Keegan, R., Hennessey, T., Marcora, S., Martin, D., Halson, S., Thompson, K. & Rattray, B. (2015). The brain of an elite athlete: Do physical training adaptations extend to the brain. Sports Medicine Australia, October 21- 24, Sanctuary Cove, Australia, (Oral).

Other Publications

1. 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), DOI: 10.3389/fphys.2015.00079.

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Abbreviations

3MT – 3 Min All-Out Cycling Test

4DMS – Four Dimensional Mood Scale

ACC - Anterior Cingulate Cortex

AM - Amotivation

ANOVA - Analysis of Variance

ATP - Adenosine Triphosphate

AX-CPT - Continuous Performance Task AX Version

BRUMS - Brunel Mood Scale

CBF - Cerebral Blood Flow

CMJ - Countermovement Jump

CON – Control

DISC - Demand Induced Strain Compensation

EEG – Electroencephalography

EMG - Electromyography

ER - External Regulation

EXT - Isometric Leg Extension

HR - Heart Rate

IM - Intrinsic Motivation

IR - Identified Regulation

IRT - Intermittent Recovery Test

LAC - Plasma Lactate

MF - Mental Fatigue

MOT - Matthew`s Overall Motivation Scale

MVC - Maximal Voluntary Contraction

NASA-TLX - National Aeronautics and Space Administration Task Load Index Scale

PASAT - Paced Auditory Serial Attention Task

POMS - Profile of Mood States

POST – Post Treatment

PPO - Peak Power Output

PRE – Pre Treatment

RPE - Rating of Perceived Exertion

RSME - Rating Scale of Mental Effort

SIMS - Situational Motivation Scale

SEM - Standard Error of the Mean

SR - Self Regulation

tDCS – Transcranial Direct Current Stimulation

TT - Time Trial

TTE - Time to Exhaustion

VAS - Visual Analogue Scale

VO_2max - Maximal Oxygen Consumption

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Chapter One: Introduction to Thesis

Introduction to Thesis

1.1 Description of Mental Fatigue

Mental fatigue is described as a change in psychobiological state caused by prolonged periods of demanding cognitive activity (Boksem and Tops 2008). Mental fatigue can be brought about by the prolonged performance of a single cognitive task, but also by the combined performance of many cognitively demanding activities, such as a working day in the office (van der Linden, Frese et al. 2003). The manifestations of mental fatigue include subjective feelings of tiredness, lack of energy and exhaustion (Watanabe, Kato et al. 2002, Boksem and Tops 2008, Marcora, Staiano et al. 2009), as well as changes in mood states, towards moods such as irritation (Broadbent 1979, Holding 1983, Holding 1983, Hockey 1997). As mental fatigue progresses, continuing a cognitive task becomes difficult, represented by aversion to continue with the present task, a decrease in the level of commitment to the task at hand (Holding 1983, Hockey 1997, Meijman 2000) and increased resistance against further effort (Meijman 2000). Anecdotal evidence has also noted that mentally fatigued persons become distracted more easily and that lapses in concentration become more frequent (Bartlett 1943).

Predictably, mental fatigue produces a detrimental effect on cognitive performance; however, the way performance is affected often varies. When completing cognitive task significant reductions in the proportion of correct responses (Marcora, Staiano et al. 2009), number of trials completed (Lorist, Boksem et al. 2005) and number of errors (van der Linden, Frese et al. 2003) has been observed with mental fatigue. The number of false alarms and missed targets tend to increase with time on task (Lorist, Klein et al. 2000, Boksem, Meijman et al. 2005), and reaction time tends to become slower (Lorist, Klein et al. 2000, Boksem, Meijman et al. 2005). It is also suggested that distinct processing functions may be affected differently by mental fatigue. For example, more complex executive functioning, such as the ability to initiate and stop actions, to monitor and change behaviour as needed, and to plan future behaviour are compromised with mental fatigue (Burgess

2011), whereas, more automatic and simple processes are not (van der Linden, Frese et al. 2003). Post-error slowing disappears with time on task (Lorist, Boksem et al. 2005) and participants correct their mistakes less often (Boksem, Meijman et al. 2006), suggesting a change in the tactical completion of tasks. The impact of mental fatigue on attention and cognitive performance has thus been well-documented (Lorist 2000, van der Linden, Frese et al. 2003, Van der Linden, Frese et al. 2003, Boksem, Meijman et al. 2005, Boksem, Meijman et al. 2006, van der Linden and Eling 2006, Cook, O'Connor et al. 2007, Lorist 2008). On the contrary, the impact of mental fatigue on subsequent physical performance remains largely unknown.

1.2 Mental Fatigue and Physical Performance

Prior to 2013, only a single study had examined the effect of mental fatigue on physical performance (Marcora, Staiano et al. 2009). This study sought to determine whether mental fatigue would impair exercise capacity in humans, following early observational data which suggested that muscle endurance was diminished in professors after long lectures and oral examinations (Mosso 1891). This 2009 study hypothesised that the prolonged performance of a cognitive task, resulting in mental fatigue, would reduce subsequent exercise capacity via an increase in cardiovascular strain. The task used to induce mental fatigue had previously been associated with significant activation of the anterior cingulate cortex (ACC), an area of the prefrontal cortex affected by mental fatigue (Fairclough and Houston 2004, Cook, O'Connor et al. 2007). The ACC has also been shown to affect autonomic control (Critchley, Mathias et al. 2003, Williamson, Fadel et al. 2006) and increase cardiovascular response during mental activity (Wright, Junious et al. 2007). Consistent with the hypothesis, this study found that mental fatigue did indeed impair exercise capacity compared to performance in a non-mentally fatigued state (Marcora, Staiano et al. 2009). In contrast to the hypothesis however, there was no effect of mental fatigue on any cardiovascular or any other physiological variable recorded. The only difference between mental fatigue and control trials was the greater rating of perceived exertion (RPE) of the mentally fatigued participants. The study concluded that perception of effort, rather than cardiorespiratory and musculoenergetic mechanisms accounted for the worse physical performance with mental fatigue.

Since then, the number of studies examining the effect of mental fatigue on physical performance has expanded, although our knowledge is still rather limited. Endurance performance in the form of both time to exhaustion tasks (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, Smith, Marcora et al. 2014) and self-paced time trial performance (MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014) have been found to worsen when participants are mentally fatigued. As has manual dexterity and anticipation timing (Duncan, Fowler et al. 2015), and performance on a soccer-specific passing test (Smith, Coutts et al. 2015). In keeping with the initial research, these studies also observed no effect of mental fatigue on physiological variables traditionally believed to limit endurance performance (oxygen consumption, cardiac output, neuromuscular function). The detrimental effect of mental fatigue on endurance performance was attributed to an increase in RPE (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014). The negative effect of mental fatigue on skilled performance was suggested to be as a result of focusing attention on irrelevant stimuli, and a reduced ability to anticipate (Smith, Coutts et al. 2015).

1.3 Thesis Aim

The overarching aim of this thesis was therefore to further investigate the effect of mental fatigue on physical performance. Within this aim, three specific research areas were identified. Firstly, at this stage, only a time to exhaustion task had been used to evaluate exercise performance. Although sufficient for initial insights, this protocol lacked ecological validity and the effects of mental fatigue on this type of task were unlikely to be transferred into a 'real-world' scenario. We therefore aimed to evaluate the effect of mental fatigue on different types of physical performance, focussing, in particular, on maximal anaerobic exercise tasks. Tasks utilising maximal strength, explosive power and anaerobic capacity were of interest as they often determine success in a sporting scenario.

Second, the participants used in the existing mental fatigue research lacked heterogeneity. Majority of the previously employed participants were described as healthy, or moderately trained. In addition, no attempt had been made to explain why mental fatigue impaired physical performance in some individuals but not others. We first compared the impact of mental fatigue on cognitive and physical performance between professional and recreational athletes. We then assessed the effect of individual lifestyle behaviours on tolerance to mental fatigue.

Third, although the research surrounding the effect of mental fatigue on physical performance is increasing, no mechanism for the increase in RPE and detriment to endurance performance has been proposed. It is important to understand the mechanisms behind mental fatigue to be able to treat and manage mental fatigue properly. Therefore, combining the findings of the previous studies, as well the findings of others who completed research concurrently, we aimed to provide a theoretical rationale for the negative effect of mental fatigue on endurance performance and RPE.

1.4 Thesis Outline

The remainder of this thesis will be presented as: (a) a critical review of the literature; (b) three original studies; (c) a hypothesis paper designed to address the thesis aims; and (d) a final discussion of the relevant findings. Each study is presented in a format for publication in peer reviewed journals and consists of its own introduction, methodology, results and discussion section. Consequently, some repetition has occurred between the introduction, literature review and the introductions of the individual chapters. To maximise coherence throughout this thesis, the reference lists from each chapter have been combined at the conclusion of the thesis. Each chapter is also preceded by a foreword designed to outline each chapter, describe how the research fits within the thesis, and how research completed by others shaped the study design.

It is also important to note that within the research and the review of the literature contained in this thesis, we define *mental fatigue* as a change in psychobiological state, caused by prolonged periods of demanding cognitive activity (Boksem and Tops 2008). A state of mental fatigue was to be accompanied by changes in subjective ratings of fatigue and changes in mood. In situations where it was not possible to determine whether a sufficient level of mental fatigue had been reached, the term *mental exertion* was used to describe the engagement with a demanding cognitive task (Rozand, Pageaux et al. 2014). This term is of particular importance in situations where decrements in performance are not observed during either a cognitive task, or subsequent physical task. This term is also important given individuals may have different thresholds for mental fatigue. The critical review of the literature was also confined to research examining the effect of a prolonged cognitive task on the performance of a subsequent physical task. Research that examined the effect of performing a cognitive and a physical task concurrently was excluded, as it is likely that changes in performance may be due to different mechanisms. Similarly, research utilising a multitude of techniques to minimise the negative effects of mental fatigue on both cognitive and subsequent physical performance were also excluded.

Chapter Two: Literature Review

Literature Review

2.1 Introduction

Mental fatigue is described as a change in psychobiological state caused by prolonged periods of demanding cognitive activity (Marcora, Staiano et al. 2009). This change is gradual and cumulative and has subjective and objective manifestations which include increased resistance against further effort (Meijman 2000), an increased predisposition towards less analytic information processing (Sanders 1998), changes in mood (Broadbent 1979, Holding 1983) and feelings of 'tiredness' and 'lack of energy' (Boksem and Tops 2008). The impact of mental fatigue on cognitive performance has been extensively explored (van der Linden, Frese et al. 2003, Boksem, Meijman et al. 2005, Boksem, Meijman et al. 2006, van der Linden and Eling 2006, van der Linden, Massar et al. 2006, Cook, O'Connor et al. 2007, Lorist 2008), however, the impact of mental fatigue on subsequent physical performance remains largely unknown. Given that many sporting contexts and occupations require high levels of both physical and cognitive exertion, and physical exertion is often undertaken during periods of mental fatigue, this literature review will focus on the impact of mental fatigue on subsequent physical performance. This literature review will discuss: (a) the methodologies used to experimentally induce mental fatigue, (b) the performance, physiological and psychological markers of mental fatigue, (c) the current literature surrounding the impact of mental fatigue on subsequent physical performance, (d) potential modulators of mental fatigue, and (e) the models of fatigue used to explain the impact of mental fatigue on physical performance. The potential mechanisms behind the impact of mental fatigue on physical performance will not be extensively discussed in this review. For a more detailed summary of these potential mechanisms please see Chapter Six.

2.2 Defining Mental Fatigue

Mental fatigue does not have a singular, universal definition, rather, a group of causes, symptoms and consequences that encompass the term. Mental fatigue has been referred to as the effects that people may experience after or during sustained cognitive activity (Boksem, Meijman et al. 2005, Lorist, Boksem et al. 2005). A phenomenon characterized by a reduction in performance after continuous cognitive workload (Watanabe, Kato et al. 2002). A state of reduced mental alertness (Grandjean 1980), and a change in psychophysiological or psychobiological state (Marcora, Staiano et al. 2009), with psychobiological referring to biological processes related to mental functioing and behaviour. Slight variations on the term mental fatigue are also utilised within the literature to describe similar occurrences. For example, the term cognitive fatigue was used to define a subjective state in which work performance declines after an extended period performing a cognitive task (Ackerman 2009). Some authors also found difficulty determining the point at which a state of mental fatigue is reached, and therefore chose to use the term prolonged mental exertion, pertaining that a sufficient level of mental fatigue may not have been reached (Pageaux, Marcora et al. 2013, Pageaux, Lepers et al. 2014, Rozand, Pageaux et al. 2014). Mental exertion is defined as engagement with a demanding cognitive task (Rozand, Pageaux et al. 2014).

Regardless of the lack of consensus on a definition of mental fatigue, it is agreed that mental fatigue is reached by prolonged periods of demanding cognitive activity (Watanabe, Kato et al. 2002, Boksem, Meijman et al. 2005, Lorist, Boksem et al. 2005, Marcora, Staiano et al. 2009), and becomes more pronounced when cognitive tasks have to be performed for long time periods without rest (Ronnback and Hansson 2004). The cognitive task used to induce mental fatigue can be the sustained performance of a single task, or can include several tasks that require cognitive effort, such as replicating a demanding day in the office (van der Linden, Frese et al. 2003). Similarly, researchers concur that the common manifestations of mental fatigue include subjective feelings of tiredness, lack of energy and exhaustion (Watanabe, Kato et al. 2002, Boksem and Tops 2008, Marcora, Staiano et al. 2009), as well as changes in mood states towards moods such as irritation (Broadbent 1979, Holding 1983, Holding 1983, Hockey 1997). As mental fatigue progresses, continuing a cognitive task becomes difficult, represented by aversion to continue with the present task (Meijman 2000), a decrease in the level of commitment to the task at hand (Holding 1983, Hockey 1997) and increased resistance against further effort (Meijman 2000). Anecdotal evidence has also noted that mentally fatigued persons become distracted more easily and that lapses in concentration become more frequent (Bartlett 1943). However, it must be noted that the acute mental fatigue associated with prolonged mental exertion and described within this literature review, is different from the chronic fatigue and cognitive impairment associated with aging or disease (e.g. cancer, chronic fatigue syndrome and depression). In these conditions, subjective feelings of fatigue and cognitive impairment are chronic and not necessarily related to mental exertion (Ahlbergm, Ekman et al. 2003, Ackerman 2011).

2.3 Inducing Mental Fatigue

To examine the effect of mental fatigue on subsequent physical performance, a state of mental fatigue must be experimentally-induced. Although a wide range of cognitive tasks have been employed to induce mental fatigue (Table 2.1), the tasks utilize a common set of traits. For example, prolonged performance of a cognitive task appears important in inducing mental fatigue. As previously stated, the task does not have to be continual performance of a single task, but can also include sustained effort invested over several tasks. In a laboratory setting, performance of a cognitive task is often able to be maintained during the first hour, but is often impaired beyond 60 min, as demonstrated by a sudden increase in reaction time (Lorist 2000). Nonetheless, subsequent physical performance has been impaired by only 30 min of mental exertion (Pageaux, Lepers et al. 2014), despite no subjective manifestations of mental fatigue being recorded. Although performance of an incongruent Stroop task for 10.5 min did not impair performance of a 20 m shuttle run test compared to performance of a congruent version of the task for the same time duration. In contrast, working long hours does not always lead to mental fatigue (Sparks, Cooper et al. 1997, Park, Kim et al. 2001), especially when the rewards of working, in terms of payment, but also appreciation by peers and co-workers, are perceived as high (Siegrist 1996, Van der Hulst and Geurts 2001).

The cognitive effort required to engage in a task also appears to play a role in the onset of mental fatigue. In particular, tasks requiring executive functioning appear most mentally demanding and as such, are capable of inducing negative effects on subsequent physical performance after only a short period of time (Pageaux, Lepers et al. 2014). Executive functioning is defined as a series of high-level processes, the main function of which is to facilitate adaptation to novel or complex situations, when highly practiced cognitive abilities or behaviour no longer suffice (Collette, Hogge et al. 2006). Executive functioning allows for effortful, complex cognition including response inhibition, planning of action, decision making and persisting at a task (Gailliot 2008). The greater level of mental fatigue produced by a task requiring executive functioning is highlighted by the higher average heart rate and slower reaction time of participants completing an incongruent Stroop colour word task, compared to a congruent Stroop colour word task (Pageaux, Lepers et al. 2014). Once mentally fatigued, it has also been reported that performance of simple, automated tasks is able to be maintained, but performance of complex tasks deteriorates (Holding 1983).

An alternative means of considering mental fatigue and physical performance research is to consider demanding cognitive tasks and endurance performance tasks as measures of self-regulation. Self-regulation is often viewed as a limited resource that enables people to override impulses, break habits and change ingrained, well-learned patterns of action (Baumeister, Bratslavsky et al. 1998, Muraven, Tice et al. 1998). Self-regulation, therefore reflects the extent to which an individual can overcome a dominant behavioural response in favour of some alternative course of action (Hagger and Chatzisarantis 2013). As this resource is finite, self-regulatory resources are hypothesized to become depleted after a period of exertion leading to decreased self-regulatory capacity. This state of diminished self-regulation has been termed 'ego-depletion' (Baumeister, Bratslavsky et al. 1998). Studies of mental fatigue mimic those of ego-depletion. Typically these studies adopt a dual-task paradigm in which participants are randomly assigned to receive an initial task that requires self-regulation (i.e. mental exertion condition) or a task that does not require self-regulation (i.e. control condition). Participants subsequently engage in a second self-regulation task (i.e. endurance exercise), performance on which constitutes the dependent measure of self-regulation. Using this model, ego-depletion has been shown to impair subsequent self-regulation in a range of unrelated domains. For example, a thought control self-regulation task reduced persistence on a subsequent anagram task (Muraven, Tice et al. 1998) and participants who were required to supress their emotions while watching an evocative video recorded shorter handgrip time to exhaustion compared to those who were able to freely express their emotions (Muraven, Tice et al. 1998). An important component of a cognitive task designed to induce mental fatigue is therefore likely to be an element of self-regulation. Many of the tasks commonly employed in mental fatigue research already require self-regulation, usually in the form of response inhibition. Further, the lack of a component of self-regulation may explain the better time trial performance of participants who completed a congruent Stroop task, compared to when they had previously completed an incongruent Stroop task (Pageaux, Lepers et al. 2014). Alongside the suggestion that a cognitive task designed to induce metal fatigue should require an element of self-regulation is the idea that the cognitive task should induce a degree of boredom, or not be completely enjoyable to complete. When a task is boring, and the person completing the task wishes to discontinue, self-regulation is required to override the urge to give up and continue with the task. A more interesting task, or one that a person finds inherently enjoyable, is more likely to be intrinsically motivating to complete, and thus mental fatigue (or a reduction in performance) may not occur. The same can be said if the reward or chance of reward for completing the task is high, mental fatigue, despite high levels of mental exertion, may not ensue (Muraven and Slessareva 2003).

The most commonly utilised cognitive tasks within the mental fatigue and physical performance literature are a modified incongruent version of the Stroop Colour Word task and the Continuous Performance task AX version (AX-CPT). Both tasks require participants to respond to a stimulus as quickly and accurately as possible, and therefore accuracy of responses and/or reaction time can be tracked throughout the intervention. The Stroop task can be performed either on a computer, where participants are required to respond by pressing a colour coded key on a keyboard (Pageaux, Lepers et al. 2014, Pageaux, Marcora et al. 2015) or by verbally responding to the stimulus (Bray, Martin Ginis et al. 2008, Bray, Graham et al. 2012, Rozand, Pageaux et al. 2014). In the computerised version of the task, four words (yellow, blue, green and red) are serially presented on a screen until the participant provides a response. Participants are instructed to press one of four coloured buttons on a keyboard (yellow, blue, green or red) with the correct response being the button corresponding to the ink colour (yellow, blue, green or red) of the word presented on the screen. For example, if the word blue appeared in yellow ink, the yellow button is to be pressed. If however the ink colour is red, the button to be pressed is the button linked to the real meaning of the word, not the ink colour (e.g. if the word blue appears in red, the button blue has to be pressed). The word presented and its ink colour is randomly selected by the computer (100 % incongruent). Participants are often familiarised with the task prior to the experimental session. In the verbal version of the task, participants are requested to read aloud, as fast as possible, a list of printed words. The same sets of conditions are applied to both tasks. In the verbal task an experimenter records the number of incorrect answers with a control sheet. Aside from the negative impact of this task on physical performance, prolonged performance of this task has also been shown to increase heart rate, and ratings of effort and mental demand in comparison to a control task (Pageaux, Lepers et al. 2014, Pageaux, Marcora et al. 2015). Prolonged performance of the Stroop task also requires the executive functions inhibitory control and sustained attention.

The AX-CPT task is also completed on a computer. In this task sequences of letters are presented one at a time on a computer screen, in a continuous fashion. Participants are instructed to press a button on the right when the letter A appears prior to the letter X. A button on the left was to be pressed for all other trials. The remaining letters of the alphabet serve as invalid cues and non-target probes, except for the letters K and Y, which are excluded because of their similarity in appearance to the letter X. Letter sequences are presented in a pseudorandom order, such that target (AX) trials occur with 70% frequency and non-target trials occur with 30% frequency. To increase task difficulty, two white distractor letters (which could be any letter but A, K, X, or Y) are presented between the cue and probe. Any missed or incorrect response elicits a bleep sound from the computer as a prompt to increase speed and accuracy. Performance of this task for 90 min has also shown to increase heart rate and subjective ratings of fatigue relative to a control condition (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, MacMahon, Schücker et al. 2014, Smith, Marcora et al. 2014). Prolonged performance of the AX-CPT task requires the executive functions working memory and sustained attention.

Author	Task	Control	Duration	Manipulation Check
Marcora (2009)	Continuous Performance Test AX Version	Documentary	90 min	↑ mean heart rate ($p=0.046$) ↑ subjective fatigue ($p=0.005$) ↓ accuracy over time ($p<0.001$)
Pageaux (2013)	Continuous Performance Test AX Version	Documentary	90 min	↑ mean heart rate ($p=0.004$) ↑ subjective fatigue ($p=0.007$)
Brownsberger (2013)	Continuous Cognitive Activity	Documentary	90 min	↑ mental fatigue ($p=0.001$) ↑β-band activation of the frontal lobe ($p=0.005$)
MacMahon (2014)	Continuous Performance Test AX Version	Documentary	90 min	↑ mean heart rate ($p=0.03$) ↑ subjective fatigue ($p=0.008$) ↓ positive mood ($p=0.049$),
Pageaux (2014)	Incongruent Stroop Task (computerised)	Congruent Stroop Task (computerised)	30 min	↑ mean heart rate ($p=0.003$) ↑ effort in MF ($p=0.042$) ↑ mental demand ($p=0.009$)
Rozand (2014)	Incongruent Stroop Task (spoken)	Congruent Stroop Task (spoken)	27 min	↑ mean heart rate ($p<0.001$) ↑ subjective fatigue ($p<0.05$) ↑ mental demand ($p<0.001$) ↑ temporal demand ($p<0.001$) ↑ physical demand ($p<0.05$) ↑ effort ($p<0.05$)
Smith (2014)	Continuous Performance Test AX Version	Documentary	90 min	↑ mean heart rate ($p=0.002$) ↑ subjective fatigue ($p=0.001$) ↓ accuracy over time ($p=0.018$)
Duncan (2015)	Concentration Grids	Documentary	40 min	Not reported
Pageaux (2015)	Incongruent Stroop Task (computerised)	Congruent Stroop Task (computerised)	30 min	↑ mean heart rate ($p<0.001$), ↑ mental demand ($p=0.012$) ↑ temporal demand ($p=0.050$) ↑ effort ($p=0.022$)
Rozand (2015)	Incongruent Stroop Task (computerised)	Documentary	90 min	↑ subjective MF ($p<0.01$) ↓ vigour ($p<0.01$)
Head (2016)	Vigilance Task (Go/No-Go)	Documentary	52 min	↑ reaction time ($p<0.001$)

Schücker (2016)	Incongruent Stroop Task (computerised)	Congruent Stroop Task (computerised)	10 min	↑ subjective fatigue (p=0.014 ↑ mental effort (p=0.006)
Smith (2016a; Study 1)	Incongruent Stroop Task (spoken)	Reading own choice of magazines	30 min	↑ subjective MF (p<0.001) ↑ mental exertion (p<0.001)
Smith (2016a; Study 2)	Incongruent Stroop Task (spoken)	Reading own choice of magazines	30 min	↑ subjective MF (p=0.016) ↑ mental exertion (p<0.001)
Smith (2016b)	Incongruent Stroop Task (spoken)	Reading own choice of magazines	30 min	↑ subjective MF (almost certain) ↑ mental effort (p=0.006)
Zering (2016)	Stop-Signal Task	Documentary	10.5 min	↑ mental exertion (p<0.001)

Table 2.1 Cognitive tasks used to experimentally induce mental fatigue. MF – Mental fatigue

2.4 Involvement of the Brain in Mental Fatigue

The negative effect that mental fatigue has on cognitive performance is well established (van der Linden, Frese et al. 2003, Boksem, Meijman et al. 2005, van der Linden and Eling 2006), however, little is known about the regions of the brain that are affected by mental fatigue, and the underlying neural mechanisms that bring about these effects. Neuroimaging studies have attempted to determine the brain regions involved in mental exertion and subsequent mental fatigue, although the findings of these studies are varied, likely due to differences in imaging techniques, as well as the cognitive tasks used to induce mental fatigue. For example, performance of a modified Paced Auditory Serial Attention task (PASAT) was significantly related to activity of the parietal, cingulate, inferior frontal and superior temporal cortices, the cerebellum and the cerebellar vermis (Cook, O'Connor et al. 2007). In this study, mental fatigue immediately following the modified PASAT task was most strongly related to activity in the posterior parietal cortex, an area associated with the short-term storage of information (Owen, McMillan et al. 2005). Performance of the Psychomotor Vigilance Task was shown to engage right-lateralized fronto-parietal network of regions (Cabeza and Nyberg 2000), and associations between a decline in cognitive performance, and a decline in regional cerebral blood flow have been observed in the sustained attention network (Cabeza and Nyberg 2000). Those who were better able to preserve performance over time, recorded smaller blood flow decreases in the right middle frontal gyrus, right inferior frontal cortex, and the anterior cingulate cortex (ACC) pre-task to post task, and less thalamic and ACC activation during cognitive task performance (Cabeza and Nyberg 2000). Furthermore, resting cerebral blood flow activity in the thalamus and right middle frontal gyrus predicted subsequent performance decline, with better-preserved performance being associated with lower resting blood flow in right middle frontal gyrus and higher resting blood flow in the thalamus (Cabeza and Nyberg 2000).

An area repeatedly suggested as being involved in mental exertion and ensuing mental fatigue is the anterior cingulate cortex. Neuroimaging studies and event related potential research have established that the ACC is central to performance monitoring (Carter, Braver et al. 1998, Gehring and Knight 2000). Activation of this area is observed when participants generate an error or when task conditions elicit high levels of task conflict (Carter, Braver et al. 1998, Ullsperger and von Cramon 2004). It has also been suggested that tasks such as the AX-CPT task (Barch, Braver et al. 1997), a task commonly employed to experimentally induce mental fatigue, is associated with significant activation of this area. Neural activity within the ACC has been found to change with time on task (Paus, Zatorre et al. 1997), suggesting that alterations in ACC functioning are a possible mechanism of mental fatigue. In addition, the monitoring function of the ACC relies on the mesencephalic dopamine system, which projects diffusely to the cortex and the striatum (Holroyd and Coles 2002). Disturbances in the striatal system have also been related to mental fatigue (Chaudhuri and Behan 2000), supporting the involvement of dopamine in mental fatigue (for further discussion please see Chapter 6, section 6.6). In terms of the effect of mental fatigue on subsequent physical performance, the ACC appears to be related to perception of effort during exercise (Williamson, McColl et al. 2001, Williamson, McColl et al. 2002), and in animal studies ACC lesions specifically affect effort-based decision making (Walton, Bennerman et al. 2003, Rudebeck, Walton et al. 2006). These behaviours are similar to those observed in a mentally fatigued human. Although the focus of this thesis does not include fatigue associated with disease, fMRI research showed that during an effortful cognitive task by patients who suffered from chronic fatigue syndrome, performance could be maintained to the same level as healthy controls, but was associated with more extensive activity in the related brain areas (Lange, Steffener et al. 2005). This study suggest that not only are specific brain regions involved in cognitive performance, but that changes in functioning are likely to also occur with mental fatigue. Plausible changes in both the functioning and metabolism of the brain with prolonged mental exertion are discussed further in Chapter 6.

2.5 Quantifying Mental Fatigue

Cognitive Performance

To establish the effect of mental fatigue on a type of performance or variable, the level of mental fatigue reached must be attempted to be quantified to compare to a control or baseline condition. As suggested by many of the proposed definitions, an acute decline in cognitive performance is often regarded as an indicator of mental fatigue. However, impaired physical performance has been detected without any significant change in the reaction time or accuracy of responses during a cognitive task. From the first to the last 15 min of 90 min of the AX-CPT task the number of correct responses declined during two studies (Marcora, Staiano et al. 2009, Smith, Marcora et al. 2014), but remained unchanged during a third (Pageaux, Marcora et al. 2013). On each occasion however, ensuing physical performance was impaired relative to performance following the control task. Similarly, 30 min of a modified incongruent Stroop task impaired subsequent 5 km treadmill time trial performance, with no change in accuracy or reaction time throughout the task (Pageaux, Lepers et al. 2014). Studies investigating the cognitive processes behind mental fatigue have more consistently demonstrated increases in reaction time throughout a number of cognitive tasks (Boksem, Meijman et al. 2005, Lorist, Boksem et al. 2005, Boksem, Meijman et al. 2006, Cook, O'Connor et al. 2007). The duration of these tasks were much greater than the cognitive tasks used in the mental fatigue and physical performance studies, and therefore it is plausible that impairments in cognitive performance may be more apparent during cognitive tasks of longer duration.

A likely mechanism for the slowed reaction time and reduced accuracy experienced during cognitive tasks of longer duration is that mentally fatigued participants appear less able to discriminate target from non-target stimuli (Boksem, Meijman et al. 2005). Selective attention mechanisms regulate which information has most impact on behaviour by enhancing processing of relevant information and suppressing irrelevant information (Boksem, Meijman et al. 2005). When mentally fatigued, participants select relevant and non-relevant stimuli for further processing, rather than only the relevant stimuli as they do when non-fatigued (Boksem, Meijman et al. 2005). This change in information processing doubles the amount of processing required to achieve the same result. Additionally, action monitoring appears impaired in mentally fatigued participants (Boksem, Meijman et al. 2006). When mentally fatigued, participants do not slowdown in responding to the next stimulus, after they commit an error, as they do in a non-fatigued state (Cook, O'Connor et al. 2007). This inability to adjust behaviour after incorrect actions is amplified in fatigued participants (Cook, O'Connor et al. 2007). With ensuing mental fatigue, participants appear to switch from a controlled, effortful strategy requiring the detection of conflict to a more passive strategy which results in an increase in overall response speed. Although mental fatigue literature is yet to fully extend to sport-based skilled performance and decision making, given the alterations in information processing and strategy that appear when mentally fatigued, it is likely that these constructs might be negatively affected. Early research involving well-trained soccer players and a soccer-specific decision-making task appears to support this hypothesis (Smith, Zeuwts et al. 2016). In this study mental fatigue impaired both speed and accuracy of soccer-specific decision-making.

Psychological Measures

A number of psychological measures have also been employed to compare between mental fatigue and control or baseline conditions. Subjective workload scales in particular are used to quantify the mental effort required to complete a given cognitive task. The National Aeronautics and Space Administration Task Load Index (NASA-TLX) rating scale (Hart and Staveland 1988) is a subjective workload questionnaire composed of six subscales; mental demand (how much mental and perceptual activity was required), physical demand (how much physical activity was required), temporal demand (how much time pressure did you feel due to the rate or pace at which the task occurred), performance (how successful do you think you were in accomplishing the goals of the task set by the experimenter), effort (how hard did you have to work to accomplish your level of performance) and frustration (how irritating or annoying did you perceive the task). The NASA-TLX is successful in discriminating between incongruent and congruent versions of the Stroop task for effort and mental demand (Pageaux, Lepers et al. 2014, Rozand, Pageaux et al. 2014), and compared to RPE, the NASA-TLX was found a more sensitive tool in identifying contributions of mental fatigue to overall perception of workload (Dragoo, Silvers et al. 2011, Mehta and Agnew 2011, Mehta and Agnew 2013).

Changes in mood also often accompany increasing mental fatigue (Holding 1983). The Brunel Mood Scale (BRUMS) (Terry, Lane et al. 2003) is a tool commonly utilised in mental fatigue literature to assess changes pre- to post- cognitive task (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, Pageaux, Lepers et al. 2014, Rozand, Pageaux et al. 2014, Smith, Marcora et al. 2014). This questionnaire, which is based on the Profile of Mood States (POMS) (McNair, Lorr et al. 1971), contains 24 items (e.g., angry, uncertain, miserable, tired, nervous, energetic) divided into six subscales: anger, confusion, depression, fatigue, tension, and vigour. The items are answered on a 5-point Likert scale (0 = not at all, 1 = a little, 2 = moderately, 3 = quite a bit, 4 = extremely), and each subscale, with four relevant items, can achieve a raw score in the range of 0 to 16. The initial version of the POMS has been well established in terms of validity and reliability (McNair, Lorr et al. 1985) and is used widely in research with clinical and normal populations including in the exercise domain (Snow and LeUnes 1994). Combined, the BRUMS and the POMS have consistently reported increases in ratings of fatigue in mental fatigue but not control conditions (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, Rozand, Pageaux et al. 2014, Smith, Marcora et al. 2014). Reductions in vigour are also often reported with both mental fatigue, and performance of a less demanding control task (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, Pageaux, Lepers et al. 2014, Rozand, Pageaux et al. 2014, Smith, Marcora et al. 2014, Pageaux, Marcora et al. 2015).

Given the subjective nature of these self-reported tools, it is important that objective measures are used in conjunction with psychological and perceptual measures to quantify mental fatigue.

Objective measures such as changes in cardiovascular variables often vary with cognitive effort and thus may help reduce any bias in self-reported measures.

Physiological Measures

Cardiovascular

Markers of physiological activity have long been proposed as indices of cognitive effort. Systolic blood pressure, diastolic blood pressure and mean arterial pressure increase with time on task, and can distinguish between periods of high and low cognitive effort (Lundberg, Kadefors et al. 1994). Heart rate is increased from baseline during both performance of mental arithmetic and a demanding video game (Turner and Carroll 1985), and heart rate variability is elevated during a task of high self-regulatory effort compared to a task of low self-regulatory effort (Segerstrom and Nes 2007). In other research fields, reduced heart rate has been suggested to be a sign of diminished alertness and thus, is suggested to have the potential for indicating driver fatigue (Hartley and Arnold 1994). Reduced heart rate variability is believed to indicate disturbed autonomic nervous system functioning (Horsten, Erigson et al. 1999) and has been associated with mental stress in laboratory experiments (Sloan, Shapiro et al. 1994, Myrtek, Weber et al. 1996). Within the mental fatigue and physical performance literature, heart rate is consistently higher during the performance of a demanding cognitive task compared to a less demanding control task (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014, Rozand, Pageaux et al. 2014, Smith, Marcora et al. 2014). During computer tasks with keystrokes at intervals of 300 ms or longer, physiological changes are believed to reflect mental effort rather than motor demands (Kohlisch and Schaefer 1996).

Electromyography

Electromyography (EMG) is a technique used for evaluating and recording the electrical activity produced by skeletal muscles. Task irrelevant EMG during a cognitive task has been proposed as an indicator of cognitive effort. Muscles are called task irrelevant if they do not directly or indirectly participate in the performance of the task-related motor activity. Task irrelevant EMG activity increases from rest during performance of the Stroop task and mental arithmetic (Lundberg, Kadefors et al. 1994), and increase further with increases in cognitive load during a simulated work day (Veldhuizen, Gaillard et al. 2003). Similarly, an increase in EMG gradient, defined as a progressive increase in frequency and amplitude of muscle action potentials (Surwillo 1956) has been interpreted as a sign of growing compensatory effort during sustained task performance (Freeman 1931, Malmo 1965). For example, sleep-deprived participants who performed worse on mathematical tasks showed small increases in EMG gradient, while those who recorded a large increase in EMG gradient were able to maintain their performance at an acceptable level (Wilkinson 1962). EMG activity of facial muscles has also shown to increase with the required speed of response during a two choice serial cognitive task (Van Boxtel and Jessurun 1993).

A number of hypotheses have been formulated to explain the increase in task-irrelevant EMG activity with increasing mental effort. It has been proposed that optimal excitation levels of the cortical centres involved in cognitive activity are maintained by the stream of afferent proprioceptive impulses from the muscles or by cerebral spread of excitation irradiating from motor centres (Freeman 1931). Suboptimal conditions, such as fatigue, would automatically lead to compensatory increases in muscle activity. The amount of task-irrelevant muscle activity would, therefore, be indicative of the degree of mental effort (Freeman 1931). Motor irradiation has also been described as a possible interpretation of the increase in facial muscle EMG activity with increasing effort in a mental task (Van Boxtel and Jessurun 1993). Motor irradiation, or motor overflow, is muscle activation that is not restricted to the muscles that are directly involved in the task, but is spread to ipsilateral and contralateral task-irrelevant muscles through spreading of activation in cortical and/or subcortical areas (Post, Bayrak et al. 2008). This can eventually lead to the recruitment of muscles with no "biomechanical utility for the task", such as the facial muscles (Gandevia 2001). In healthy adults, motor overflow is usually seen only during tasks requiring considerable effort, and generally occurs in an automatic and unintentional way (Hoy, Fitzgerald et al. 2004). EMG gradients have been reported in forearm extensors and flexors during inductive thinking (Davis 1938), mental arithmetic (Davis 1939) and simple reaction time (Eason and Dudley 1971).

Electroencephalography

Electroencephalography (EEG) is the measurement of the electrical activity of the brain by recording from electrodes placed on the scalp. During studies of EEG four major types of EEG activity are recognized; alpha, beta, delta and theta. EEG is sensitive to fluctuations in vigilance and has been shown to predict deterioration in cognitive performance due to sustained mental work (Lal and Craig 2001). During a 3 h visual attention task, alpha, theta, and beta power are increased (Boksem, Meijman et al. 2005). Changes in alpha and theta waves have also been related to impaired performance during a sustained auditory detection task (Makeig and Jung 1995). During and after a 45 min and 90 min performance of the AX-CPT task beta activity in the frontal lobe was elevated compared with the control condition at the same time point, as well as during the warm-up during subsequent exercise performance (Brownsberger, Edwards et al. 2013). The authors suggested that sustained elevation of beta activity in the frontal lobe during the mental fatigue task indicated that the AX-CPT was successful in eliciting greater attention, information processing and cognitive engagement (Lorist 2000, Nielsen, Hyldig et al. 2001, Crabbe and Dishman 2004, Lorist, Bezdan et al. 2009). EEG appears to be a promising area of investigation for mental fatigue research. With advances in the practicality, ease and portability of the technology used to record EEG, research examining EEG during exercise in a mentally fatigued state will improve.

Eye Movement

Another promising measure of mental fatigue is the analysis of eye movement during a task. Given the rich sensory and motor connections between the eye and the brain, eye movement can provide a valuable warning sign of drowsiness. With increasing fatigue during a driving simulation task, fast eye movement and conventional blinks in an alert state become replaced by no eye movement and small, fast, rhythmic blinks (Lal and Craig 2001). Although this measure does not specifically quantify cognitive effort, analysing eye movements appears a reliable sign of drowsiness, which is a characteristic of impending mental fatigue. Changes in pupil diameter are also believed to be associated with changes in cognitive load (Beatty 1982). The pupil, which can vary in size from 0.2 to 0.8 mm, is controlled by a set of antagonistic muscles in the iris. One muscle group, the dilator pupillae, is innervated by fibres from the sympathetic nervous system. Stimulation of this muscle causes a retraction of the iris, thereby increasing the size of the pupil. The second muscle group, the sphincter pupillae, is innervated by fibres from the parasympathetic nervous system. Stimulation of this muscle expands the iris, thereby decreasing the size of the pupil (Kramer 1991). The magnitude of the pupillary dilation appears to be a function of the mental effort required to perform a task (Beatty 1982). Task-evoked pupillary response has shown to be sensitive enough to distinguish between levels of task difficulty, as well as the difference in cognitive effort required by experts and novices to answer a question in their chosen field (Szulewski, Roth et al. 2015).

Blood Glucose Concentration

Activities of the brain rely heavily on glucose for energy (Siesjo 1978, Weiss 1986) and metabolism of glucose allows the brain to carry out its given functions. Mental fatigue literature has attempted to quantify cognitive effort by measuring changes in blood glucose concentration over the duration of a task, and examining differences between mental fatigue and control conditions. Although glucose concentration was reported to decline over the duration of a mentally fatiguing cognitive task, no significant difference was observed compared to the control condition (Marcora, Staiano et al. 2009, Pageaux, Lepers et al. 2014). In addition, glucose concentration was similar between conditions and remained steady in team sport athletes who completed 90 min of the AX-CPT and a control task (Smith, Marcora et al. 2014). Despite contradicting results in mental fatigue and physical performance literature, within psychology research, blood glucose concentration has often been reported to be reduced with cognitive effort, and be sensitive to both time on task (Fairclough and Houston 2004) and the complexity of the task (Benton, Owens et al. 1994, Kennedy and Scholey 2000, Fairclough and Houston 2004). Blood glucose levels reduced from baseline during an attention regulation task and were lower compared to participants who had completed a time-matched control task (Gailliot, Baumeister et al. 2007). Participants who were required to engage in a high self-regulatory task depleted blood glucose levels to a greater extent than those who participated in a low self-regulatory task (Gailliot, Baumeister et al. 2007) and blood glucose concentration fell more rapidly during the performance of a complex cognitive task compared to a simple cognitive task (Scholey, Harper et al. 2001). Although peripheral blood glucose is not a direct measure of brain metabolism, brain glucose levels in rats have previously been correlated with blood glucose levels (Matsui, Soya et al. 2011), and brain glycogen levels during exercise are positively correlated with both blood and brain glucose levels (Matsui, Soya et al. 2011). However, reductions in blood glucose with the expenditure of cognitive effort or self-regulation are not reported consistently (Pageaux, Lepers et al. 2014) and some doubt has been cast on the likelihood of glucose being a limiting factor for tasks of self-regulation (Kurzban 2010). To date, assessing changes in blood glucose concentration with mental fatigue has not been the primary focus of any study, therefore variations in the testing protocol and methodology for assessing blood glucose does not allow for true evaluation of the suitability of blood glucose concentration as an indicator of mental fatigue. Further, with advancements in technology it may soon be possible to quantify more direct changes in brain metabolism during mental exertion.

Cerebral Blood Flow and Oxygenation

Brain function is dependent on delivery of blood-borne metabolic substrates to active tissue. At the onset of a demanding cognitive task, oxygen consumption and cerebral blood flow (CBF) increase in a response to neural activation, at the end of the task oxygen consumption and CBF are reduced (Li, Zhang et al. 2009). During prolonged cognitive activity, energy demand can exceed energy supply and an imbalance can occur in the activated brain regions (Rupp and Perrey 2008). Technologies such as near-infrared spectroscopy, transcranial Doppler, positron emission tomography and functional magnetic resonance imaging are increasingly being used to examine brain function by allowing us to measure changes in CBF, cerebral blood flow velocity and cerebral oxygenation. Significant increases in oxyhaemoglobin and total blood volume in the left frontal lobe were recorded at the onset of a simulated driving task compared with resting values (Li, Zhang et al. 2009). Following 3 continuous hours of the task, oxygen saturation was significantly decreased, and participants reported symptoms of fatigue including tiredness, irritability and lack of energy (Li, Zhang et al. 2009). A significant negative correlation between cerebral oxygen saturation and reaction time during the task was also observed, suggesting that cerebral oxygenation may be an important contributor to the development of mental fatigue (Li, Zhang et al. 2009). An individual's ability to better preserve cognitive performance over time was associated with smaller CBF decreases in the right middle frontal gyrus, right inferior parietal cortex and anterior cingulate cortex from pre-task to post-task (Lim, Wu et al. 2010). This finding was similar to observations within sleep deprivation literature suggesting that baseline cortical activity is associated with cognitive vulnerability during periods of sleep loss (Mu, Mishory et al. 2005). CBF velocity was also positively correlated with task engagement during a sustained attention task (Matthews, Warm et al. 2010), and as such CBF velocity declined in parallel with the number of correct responses during the task. Although this research appears promising, the affordability, portability and sensitivity of these measures to movement may not be conducive to a practical measure of mental fatigue. However, research investigating the susceptibility of individuals to mental fatigue is likely to be useful in a number of occupational and performance settings.

Summary of Quantifying Mental Fatigue

A number of methodologies have been used in an attempt to quantify mental fatigue. These measures include changes in cognitive performance, psychological ratings of subjective workload and fatigue, and physiological measures including peripheral variables such as heart rate and EMG gradients as well as direct variables emanating from the brain such as blood flow and EEG measures. Within the mental fatigue and physical performance literature heart rate during a cognitive task (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014, Rozand, Pageaux et al. 2014, Smith, Marcora et al. 2014) and ratings of subjective fatigue (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, MacMahon, Schücker et al. 2014, Rozand, Pageaux et al. 2014, Smith, Marcora et al. 2014, Smith, Coutts et al. 2015) and workload (Pageaux, Lepers et al. 2014, Rozand, Pageaux et al. 2014, Pageaux, Marcora et al. 2015, Smith, Coutts et al. 2015) are most commonly employed, as well as appear to be most sensitive. The benefits of these measures are their ease of use and affordability. The practicality and purpose of quantifying mental fatigue may also be different in different scenarios and therefore the methods used to quantify mental fatigue may change. As observed within the literature, it is also important to pair subjective psychological measures with objective physiological measures. Subjective psychological variables are subject to response bias, as well as differences between individuals in magnitude of responses or perceptions. Physiological variables of mental exertion or mental fatigue are very difficult, if not impossible to manipulate consciously. It is therefore advised to include physiological data to strengthen the findings of perceptual data.

Finally, the term mental fatigue in this context must be used with caution. Participants may reach mental fatigue at different stages and after different amounts of mental exertion, or not at all. It may be more accurate to term some of these measures methods of quantifying mental exertion, as opposed to quantifying mental fatigue, particularly when some individuals do not display any impairment in subsequent cognitive or physical performance. This conundrum however, is unlikely to be resolved until a universal and definitive definition of mental fatigue is proposed.

2.6 Effect of Mental Fatigue on Physical Performance

The effect of mental fatigue on different types of physical performance are summarised in Table 2.2.

Endurance Performance

The research completed to date suggests that prolonged endurance exercise is most affected by mental fatigue. In previous research, as well as the proceeding thesis, endurance performance is defined as dynamic exercise that involves continuous effort and lasts for 75 s or longer (McCormick, Meijen et al. 2015). Time to exhaustion during both cycling at 80% peak power output (Marcora, Staiano et al. 2009) and a single leg isometric knee extension at 30% of maximum (Pageaux, Marcora et al. 2013) was reduced following 90 min of the AX-CPT task. Performance of a 5 km treadmill time trial (Pageaux, Lepers et al. 2014) and a 3km running track time trial (MacMahon, Schücker et al. 2014) were worse following a mental exertion task compared to a control task. Less work was produced during a 6 min (Pageaux, Marcora et al. 2015) and 10 min submaximal cycling bout (Brownsberger, Edwards et al. 2013) when mentally fatigued. The distance run during two intermittent running protocols were reduced following a demanding cognitive task compared to a control (Smith, Marcora et al. 2014, Smith, Coutts et al. 2015), and peak power output during a graded exercise task was lower following a short bout of mental exertion (Zering, Brown et al. 2016). Performance on a 20 m shuttle run test did not differ following 10 min performance of an incongruent Stroop task compared to following 10 min of either a congruent Stroop task or 10 min spent watching a video (Schücker and MacMahon 2016). Notably, the duration of the cognitive task in this study was shorter than the duration of the cognitive tasks typically designed to induce a state of mental fatigue. However, decrements in physical performance have observed following performance of cognitive tasks of similar duration (Zering, Brown et al. 2016). In addition, both subjective ratings of cognitive fatigue and average heart rate where higher during the fatiguing versus the control cognitive task. The authors of this study suggested that as participants were aware of their level of performance, this could lead to high levels of motivation, with participants wanting to match or beat their performance in the second trial regardless of the intervention completed. The effect of manipulations of motivation on mental fatigue are further discussed later in this chapter (Section 2.8). Zering and colleagues also suggested that the likely high self-regulatory capacity of the well-trained participants may have created a buffer for decrements in physical performance typically observed following mental exertion. This line of thought is the focus of Chapters Four and Five.

When participant's complete endurance tasks following a bout of mental exertion, variables traditionally believed to limit endurance performance, such as heart rate, lactate accumulation, oxygen consumption, neuromuscular function and peripheral fuel availability appear unaffected by mental fatigue. Rather, the worse performance of mentally fatigued participants has been attributed to an increase in RPE (Marcora, Staiano et al. 2009, Brownsberger, Edwards et al. 2013, Pageaux, Marcora et al. 2013, MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014). During a time to exhaustion task, mentally fatigued participants reach their maximum RPE faster and disengage from the task earlier than they do in a control condition (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013). During a time trial when mentally fatigued, RPE is kept consistent between conditions, with power output or speed down-regulated to ensure a sustainable RPE for the duration of the trial (Brownsberger, Edwards et al. 2013, MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014). Mental fatigue however, does not affect pacing. It has previously been noted that participants tend to alter their work output during self-paced exercise so that their RPE remains relatively constant (Cole, Costill et al. 1996). The mechanism behind the increase in RPE when mentally fatigued is therefore important. Strategies to reduce RPE when mentally fatigued may also improve subsequent endurance performance.

High-Intensity Performance

Compared to prolonged endurance exercise, fewer studies have examined the effect of mental fatigue on short-duration, high-intensity and anaerobic exercise performance. These studies, although limited, have not found any effect of mental fatigue on this type of exercise performance. Maximal voluntary contractions of the knee extensor muscles were not different from a control condition following performance of the AX-CPT task (Pageaux, Marcora et al. 2013) or an incongruent Stroop task (Rozand, Pageaux et al. 2014, Pageaux, Marcora et al. 2015). The high-intensity component of an intermittent running protocol was unchanged between mental fatigue and control conditions (Smith, Marcora et al. 2014), and power output during four repeated Wingate tests was unaffected by prior mental exertion (Duncan, Fowler et al. 2015). There are a number of factors which may explain the disparity in the negative impact of mental fatigue on endurance and anaerobic exercise performance. Prolonged endurance exercise can be limited by both central fatigue, a progressive reduction in voluntary activation of muscle during exercise (Gandevia 2001), as well as peripheral fatigue, fatigue produced by changes at or distal to the neuromuscular junction (Gandevia 2001). In contrast, short-duration and high-intensity anaerobic tasks are primarily modulated by peripheral fatigue. The contribution of a conscious pacing strategy between endurance and anaerobic exercise performance also differs. Pacing is defined as the efficient use of energetic resources during athletic competition, so that all available energy stores are used before finishing a race, but not so far from the end of a race that a meaningful slowdown can occur (Foster, de Koning et al. 2003). A number of models have suggested that pacing is regulated by the brain for prolonged endurance exercise (Marcora 2008, Noakes 2012), while short-duration anaerobic tasks are less influenced by pacing strategy than metabolic fatigue. Prolonged endurance tasks require a constant and conscious drive to continue to exercise, continually regulating pace based on RPE, among other things. On many occasions, physical tasks require an all-out effort, with no regard for future efforts. During these tasks the cognitive component of pacing and self-regulation is less important and peripheral feedback and the functional component of the bodies' capacity comes to the forefront, leaving less scope for RPE to influence behaviour. Given the importance of short-duration and maximal intensity efforts, and strength and power in the performance outcomes of many sports, it is surprising that little research has been conducted in this area. Many sporting contexts also utilize high-intensity efforts interspersed by prolonged endurance exercise. Studies that are more applicable to real-life sporing situations, and replicate the demands of a game would therefore be of more relevance to many team-sport athletes and coaches.

Skilled Performance

Research investigating the impact of mental fatigue on skilled performance is particularly scarce. Early researchers suggested that among the processes affected by mental fatigue, was the coordination and accurate timing of tasks (Bartlett 1943). Mental fatigue does not affect maximal strength (Pageaux, Marcora et al. 2013, Rozand, Pageaux et al. 2014), however, the EMG activation required to generate and sustain a submaximal force was affected by prior mental exertion (Bray, Martin Ginis et al. 2008). An increase in EMG activation may represent an increase in motor unit recruitment to carry out a movement. Several muscles contribute to the production of an action, and when individual muscles are analysed, it cannot be determined whether an increase in EMG activation is representative of an increase in activation of the total muscle group or whether the increase of motor unit recruitment of one muscle is to supplement decreased activation of another. Individual muscles within a muscle group co-contract to stabilise a joint and create an efficient movement pattern (Ford, van den Bogert et al. 2008). It is possible therefore, that complex, dynamic movements may be affected by mental fatigue.

The effect of mental fatigue on manual dexterity and coincidence anticipation has also been examined in order to better replicate perceptual and motor skills which are a feature of many sports and activities (Duncan, Fowler et al. 2015). Mental fatigue negatively impacted on manual dexterity and coincidence anticipation timing performance compared with a passive observation control condition (Duncan, Fowler et al. 2015). Although this is the first study to examine the effect of mental fatigue on these types of variables, previous research has shown similar negative effects on related cognitive and perceptual skills including visual selective attention (Faber, Maurits et al. 2012), reaction time (Langner, Steinborn et al. 2009) and simulated driving performance (Fischer, Langner et al. 2008). The findings of impaired manual dexterity and coincidence anticipation with mental fatigue were suggested to be in line with the ego-depletion model which proposes self-regulating effort on one task can diminish effortful performance on subsequent tasks provided both tasks require some form of emotional, cognitive or physical effort regulation. However, within the same study, four repeated Wingate cycling tests were unaffected by mental fatigue suggesting that other mechanisms may be involved in regulating physical effort following mental exertion.

Finally, following 30 min performance of the Stroop task, participants committed more passing and ball control errors, and performed slower and less accurate shots on goals during a soccer skill specific test (Smith, Coutts et al. 2015). These findings supported reductions in the quality and quantity of technical performance observed towards the end of a soccer match (Rampinini, Impellizzeri et al. 2008, Carling and Dupont 2011). Similar increases in errors have also been observed with mental fatigue during other skilled tasks, such as driving (Lal and Craig 2001, Boksem, Meijman et al. 2005). Previous research has suggested that mental fatigue leads to impaired performance monitoring and inadequate performance adjustment during cognitive tasks (Lorist, Boksem et al. 2005). An inability to identify errors, and adjust accordingly may explain the increase in errors with time on task. Similarly, mental fatigue is believed to cause a change in attention from goal-directed stimuli, toward stimuli unrelated to task performance (Boksem, Meijman et al. 2005). The negative effect of mental fatigue on soccer-specific technical performance may therefore be related to the focussing of attention on irrelevant stimuli and a reduced ability to anticipate the movement of the ball and prepare to control it. In a professional sporting scenario, this effect may be exacerbated with the addition of the crowd, advertising, media and extra noise. Further research into more sport specific and situation specific scenarios is therefore important.

Author	Participants	Physical Task	Performance Outcomes
Marcora (2009)	n=16 (10 male, 6 female) 26±3 years VO_{2MAX} 52±8 $ml.kg^{-1}.min^{-1}$	Cycling TTE (80% peak power)	↓ TTE (p=0.003)
Pageaux (2013)	n=10 (10 male) 22±2 years Physically active	Single-leg isometric contraction TTE (20% MVC)	↓ TTE (p=0.008),
MacMahon (2014)	n=20 (18 male, 2 female) 25±3 years Ran on average 2.84 hr/week	3 km running TT (track)	Slower TT (p=0.009) No change in pacing strategy
Smith (2014)	n=10 (10 male) 22±2 years VO_{2MAX} 48±6 ml.kg-1.min^{-1} Team sport athletes	Intermittent high-intensity running protocol (45 min)	↓ Low-intensity velocity (p=0.038) ↓ Low-intensity distance (p=0.02) No effect on high-intensity velocity No effect on high-intensity distance
Brownsberger (2013)	n=12 (8 male, 4 female) 24± 5 years VO_{2MAX} 56±6 ml.kg.$^{-1}min^{-1}$	2 x 10 min cycling at RPE of 11 and RPE of 15	↓ mean power for RPE 11 (p=0.005) ↓ mean power for RPE 15 (p=0.028)
Duncan (2015)	n=8 (7 male, 1 female) 25±4 years >10 hr/week of exercise	4 x 30s Wingate cycling tests Minnesota Manual Dexterity Turning Test Bassin anticipation timer test	↓ manual dexterity (p=0.03) ↓coincidence anticipation timing (p=0.028) No effect on Wingate test performance
Pageaux (2014)	n=12 (8 male, 4 female) 21±1 years 2 x per week aerobic exercise	5 km running TT (treadmill)	Slower TT (p=0.008) No change in pacing strategy
Rozand (2014)	n=10 (10 male) 25±1 years Healthy and active	Single-leg intermittent MVC	No effect on MVC
Pageaux (2015)	n=12 (12 male) 25±4 years 2 x per week moderate exercise	Single-leg knee extension MVC	No effect on MVC
Rozand (2015)	n=10 (10 male) 24±2 years Healthy, with normal vision	Arm pointing task (Whilst sitting participants had to point between two targets with their dominant hand)	↑ Movement duration (p<0.001)

Head (2016)	n=18 (11 male, female 7) 28±4 years > 6 months participating in HIT	High intensity body resistance exercise circuit (5 pullups, 10 push ups, 15 squats) Maximum repetitions completed in 20 min	No difference in repetitions (p=0.772) ↓ Time-on-task (p=0.037)
Schücker (2016)	n=12 (3 male, 9 female) 29±14 years 8±4 hours training per week	20 m Shuttle Run Test	No difference in distance covered between conditions (Study 1, p=0.60, Study 2, p=0.84)
Smith (2016)	n=26 (26 male) 22±2 years 12 recreational soccer players 14 well-trained soccer players	Yo-Yo IRT (Level 1) Loughborough Soccer Passing Test Loughborough Soccer Shooting Test	↓ Distance covered (p<0.001) ↑ Penalty time (p<0.05)

Table 2.2 Effect of mental fatigue on physical performance measures. VO2MAX; maximal oxygen uptake, TTE; time to exhaustion, TT; time trial, MVC; maximal voluntary contraction, IRT; intermittent recovery test, RPE; rating of perceived exertion, HIT: high intensity traini ng

2.7 Mental Fatigue and Physiological Variables during Exercise

Although mental fatigue alters several physiological variables during the performance of a demanding cognitive task, few of these variables remain changed from baseline during a subsequent exercise task. It was originally hypothesised that prior mental activity involving the ACC, an area of the prefrontal cortex affected by mental fatigue (Lorist, Boksem et al. 2005, Cook, O'Connor et al. 2007), would increase cardiovascular strain during exercise, and thus impair performance (Marcora, Staiano et al. 2009). This was based on evidence that the human cingulate cortex plays an important role in autonomic control during effortful cognitive and motor tasks (Critchley, Mathias et al. 2003). Within the mental fatigue literature, heart rate is consistently recorded as higher during the performance of a fatiguing cognitive task compared to a control task (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014, Smith, Marcora et al. 2014, Pageaux, Marcora et al. 2015). However, the higher average heart rate during the fatiguing task does not transfer to higher heart rate during a subsequent exercise task. Other cardiovascular measures including stroke volume, cardiac output and mean arterial pressure are also not different between mental fatigue and control conditions (Marcora, Staiano et al. 2009). As such, increased cardiovascular strain cannot be attributed to impaired endurance performance when mentally fatigued.

EMG activity has also shown to increase alongside increases in cognitive effort (Lundberg, Kadefors et al. 1994). EMG gradients have generally been interpreted as a sign of growing compensatory effort during sustained task performance, counteracting detrimental effects of fatigue (Freeman 1931, Malmo 1965). Although not specifically examining mental fatigue, performance of the Stroop colour word task simultaneously with a static contraction of the trapezius muscle significantly increased EMG activity compared to the contraction alone (Lundberg, Kadefors et al. 1994). EMG activity was also increased during a handgrip endurance task following a short bout of cognitive effort (Bray, Martin Ginis et al. 2008). Recent research has hypothesised that prolonged mental exertion would reduce maximal muscle activation and increase the extent of central fatigue induced by subsequent endurance exercise (Pageaux, Marcora et al. 2013), explaining the negative effect of mental fatigue on endurance performance. Contrary to the hypothesis, prolonged mental exertion did not lead to any impairment in neuromuscular function (Pageaux, Marcora et al. 2013).

Plasma lactate concentration (Marcora, Staiano et al. 2009, MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014, Smith, Marcora et al. 2014, Duncan, Fowler et al. 2015) and plasma glucose concentration during exercise are also unaffected by mental fatigue (Smith, Marcora et al. 2014) and therefore do not contribute to the observed worse endurance performance.

2.8 Mental Fatigue and Psychological Variables during Exercise

In contrast to physiological variables, psychological variables that are altered with mental fatigue appear to contribute to the impaired endurance performance of mentally fatigued participants. In particular, the greater RPE experienced by mentally fatigued participants for a given workload, is thought to be the primary mechanism by which mental fatigue impairs endurance performance (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, Pageaux, Lepers et al. 2014, Smith, Marcora et al. 2014). Prolonged mental exertion is hypothesized to act on the cortical centres of the brain involved in the cognitive aspects of central motor command (Hallett 2007) and the primary sensory input for perceived exertion (Marcora 2008). More specifically, one of the key areas of the cortical centre involved is believed to be the ACC, an area of the prefrontal cortex strongly activated by cognitively demanding tasks (Paus, Koski et al. 1998). Functions that have been ascribed to the ACC include cognition, emotion, error detection, human perception and behaviour (Bush, Luu et al. 2000). The ACC is believed to play a role in the distribution of effort, based on predicted rewards. Rats with experimental ACC lesions engage significantly less in tasks requiring physical effort, to obtain a larger reward (Paus, Koski et al. 1998, Rudebeck, Walton et al. 2006). In humans, changes in the activation of the ACC correlate with changes in RPE during manipulations of exercise intensity under hypnosis and motor imagery (Williamson, McColl et al. 2001, Williamson, McColl et al. 2002).

With prolonged mental exertion, it is believed extracellular concentrations of adenosine accumulate in the ACC, and this accumulation is responsible for the greater RPE experienced by mentally fatigued participants (Pageaux, Lepers et al. 2014). This hypothesis is discussed further in Chapter Six.

Both behavioural and mood changes associated with mental fatigue also suggest that motivation may be impaired with prolonged mental exertion. A central component of mental fatigue is described as an 'increased resistance to further effort' (Meijman 2000) and a 'decrease in the level of commitment to the task at hand' (Holding 1983, Hockey 1997, Meijman 2000), however, few studies have reported a reduction in self-rated motivation with mental fatigue. Motivated behaviours can be characterised by vigour, persistence and high levels of work output (Salamone and Correa 2009). Reductions in these characteristics are commonly reported with mental fatigue. For example, mood and particularly measures of vigour and subjective fatigue are decreased and increased respectively (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013) following prolonged mental exertion. Participants disengage earlier from a task when they are mentally fatigued (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013) and power output or speed during a time trial is down-regulated (MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014, Smith, Marcora et al. 2014). Aversion to continue the task at hand is increased with time on task (Boksem, Meijman et al. 2005), and response rate is slowed (Boksem, Meijman et al. 2005). Furthermore, participants report a reduced willingness to exert further effort (van der Linden, Frese et al. 2003). Although not during exercise performance, a monetary reward was able to improve either reaction time or accuracy in participants who had completed a cognitive task for 2 hours previously (Boksem, Meijman et al. 2006). Monetary incentives during an isometric handgrip to exhaustion also counteracted the deleterious effects of mental fatigue on time to exhaustion, as well as facilitated performance compared to non-fatigued controls (Brown and Bray 2016). These studies suggest that when sufficiently motivated, participants may be able to overcome the detrimental effects of mental fatigue to an extent.

2.9 Modulators of Mental Fatigue

The impact of mental fatigue on cognitive and physical performance, as well as subjective psychological markers are reasonably consistent, however, there are several factors that appear to modulate typical characteristics of mental fatigue. The following are factors which need to be considered when designing a study of mental fatigue, or considering possible methods by which to lessen the impact of mental fatigue on both cognitive and physical performance.

Caffeine

Ingestion of caffeine, a socially acceptable and legal drug, has shown to reverse some of the effects of mental fatigue on cognitive performance, psychological changes and physical performance. The stimulatory effect of caffeine is believed to stem from its ability to antagonize the actions of adenosine (Dunwiddie and Masino 2001), and as such caffeine has also proved effective at improving both cognitive and physical performance decrements during periods of sleep deprivation. Caffeine reduced the impairment in cognitive performance during a dual cognitive and physical task compared to a placebo (van Duinen, Lorist et al. 2005) and lessened ratings of subjective mental fatigue during a prolonged mental exertion task (Kennedy and Scholey 2004). Caffeine helped maintain cognitive performance during sleep deprivation (Penetar, McCann et al. 1993), as well as increases alertness and improve mood (Wesensten, Belenky et al. 2002). In a physical performance setting, ingestion of caffeine increased total work performed when participants were asked to cycle at a given RPE compared to a placebo (Cole, Costill et al. 1996). Caffeine increased time to exhaustion and reduced RPE following 28 hours of sleep deprivation (McLellan, Bell et al. 2004), and improved time to exhaustion compared to both a placebo and the control trial (Azevedo, Silva-Cavalcante et al. 2016). In the study by Azevedo and colleagues, despite improved endurance performance with caffeine ingestion, no significant differences were observed between control, placebo and caffeine trials for any cardiorespiratory, metabolic or neuromuscular variable. It was therefore suggested that the effect of caffeine on endurance performance is mainly mediated through a modulation in central nervous system (CNS) function (Azevedo, Silva-Cavalcante et al. 2016). The ability of caffeine to counteract the negative effects of mental fatigue have previously been suggested to be due to the blockade of adenosine receptors in the CNS (Smith, Sutherland et al. 2005, Spriet 2014), as well as a reduction in RPE (Cole, Costill et al. 1996), thereby enabling participants to perform a greater amount of work. For further discussion of the role of adenosine and caffeine in mental fatigue presentation please see chapter six.

Motivation

Manipulating motivation may also confound the effect of mental fatigue on both cognitive and physical performance. Studies have shown that when sufficiently motivated mentally fatigued participants are able to improve their performance back to, or near baseline levels. Social comparison and a monetary reward were used to experimentally increase extrinsic motivation in mentally fatigued participants (Lorist, Bezdan et al. 2009). With time on task, reaction time and inaccuracy was increased, however, following the manipulation a significant improvement in reaction time was observed (Lorist, Bezdan et al. 2009). Cognitive performance of both young and older adults who were paid to participate in a study did not change over 60 min performance of a cognitive vigilance test (Tomporowski and Tinsley 1996). In contrast, young adults who were not paid for their participation recorded significant decrements in cognitive performance (Tomporowski and Tinsley 1996). Motivation has also shown to improve physical performance. Competing against an avatar of themselves or a partner improved performance during a cycling time trial (Wilmore 1968, Corbett, Barwood et al. 2012). The duration of time to exhaustion during an isometric contraction increased linearly in relation to the amount of money the participant would earn for completing the task (Cabanac 1986) and motivational self-talk reduced RPE and improved endurance performance during a cycling task (Blanchfield, Hardy et al. 2013). More specifically, examining the effect of motivation on the impact of mental fatigue on physical performance, in mentally fatigued participants a financial incentive improved handgrip time to exhaustion to above that of a control group, and a no-incentive mentally fatigued group (Brown and Bray 2016). The effect of motivation must therefore be controlled during testing of endurance performance and mental fatigue research should consider intentional and unintentional modes of motivation present when analysing performance data over time. The knowledge of, and timing of, methods of payment or reward for participation must be considered, as well as consideration of the testing environment. For example, the presence of an attractive female research assistant reduced RPE during a running time trial at 60% of peak running speed in males, compared to the presence of a male research assistant (Winchester, Turer et al. 2012). Manipulations of motivation may also be considered in future research when examining methods to overcome the negative effect of mental fatigue on physical and cognitive performance. However, it is likely that the novelty and or benefit of any 'reward' or 'incentive' may be reduced over time.

Sleep

The duration a participant has slept for in the days leading up to a trial, may also affect the impact of mental fatigue on physical performance. Studies of sleep deprivation suggest that lack of sleep has similar effects on cognitive and physical performance as mental fatigue. Thirty-six hours of sleep deprivation increased RPE and reduced time to exhaustion during prolonged treadmill walking (Martin 1981). RPE progressively increased during a treadmill task with increasing duration of sleep loss (Myles 1985). Distance covered during a self-paced intermittent running protocol was reduced after 30 hours of sleep deprivation (Skein, Duffield et al. 2011) and distance covered in a 30 min running time trial was lower following 30 h without sleep, compared to a normal night's sleep (Oliver, Costa et al. 2009). During these trials RPE was not different between conditions, meaning that a slower running or walking speed was maintained for the same RPE in the sleep deprivation trial compared to the control trial, an observation consistent with physical performance and mental fatigue literature. Restricted or disturbed sleep in elite athletes is also associated with impairments in mood and motivation (Sinnerton and Reilly 1992). Conversely, increasing the amount of sleep of college basketball players improved sprint time and shooting accuracy, compared to baseline and 'normal' (≈8 h per night) sleep (Mah, Mah et al. 2011) and a daytime nap was more effective than resting in a waking state at improving cognitive performance following 90 min of mental exertion (Puchkova, Tkachenko et al. 2013). The mechanism behind the apparent restorative effect of sleep on fatigue is unclear. Sleep has been suggested to restore brain glycogen (Brown 2004), remove potentially neurotoxic waste (Xie, Kang et al. 2013) and regulate gene expression (Archer, Laing et al. 2014). Whether or not these mechanisms play a role in the performance improving or restoring effects of sleep, it is likely that disrupted sleep will impair subsequent cognitive and physical performance. Studies of mental fatigue must therefore ensure participants complete all testing sessions at the same time of day, and record sufficient sleep in the days leading up to the experimental trials.

Modafinil

Modafinil is a central nervous system wake-promoting drug that modulates multiple neurotransmitters, elevating levels of dopamine, noradrenaline, glutamate and serotonin and decreasing gamma-aminobutyric acid levels (Minzenberg and Carter 2008, Volkow, Fowler et al. 2009). Modafinil is used clinically in the treatment of narcolepsy (Boivin, Montplaisir et al. 1993), but is widely prescribed for off-label use in conditions involving fatigue or cognitive dysfunction (Davies, Wilton et al. 2013). Modafinil has been reported to reduce fatigue in patients with multiple sclerosis (Zifko, Rupp et al. 2002), improve fatigue, alertness and cognitive performance in sleep deprived participants (Baranski, Cian et al. 1998) and increase cycling time to exhaustion compared to a placebo (Jacobs and Bell 2004). The mechanisms of action of Modafinil are unknown (Ballon and Feifel 2006). Modafinil is suggested to reduce gamma-aminobutyric acid, a major inhibitory neurotransmitter (Ballon and Feifel 2006), as well as be a weak dopamine reuptake inhibitor. Whatever the mechanism of Modafinil, its effect on fatigue, cognition and physical performance are likely to affect the impact of mental fatigue on performance. Modafinil, as well as other manipulators of dopamine, or psychostimulant drugs must be controlled for or avoided in studies of mental fatigue.

2.10 Models of Fatigue to Explain the Impact of Mental Fatigue on Performance

Psychobiological Model

The Psychobiological Model of Exercise Tolerance (Marcora 2008) is the most common model used to explain the impairment of endurance performance with mental fatigue (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014). This model is convenient for the phenomenon of mental fatigue as it utilises both biological and psychological factors to explain performance. The model, based on motivational intensity theory (Brehm and Self 1989, Wright 2008), proposes that the point at which one stops exercising is determined primarily by RPE and potential motivation. RPE is defined as the conscious sensation of how hard, heavy and strenuous a physical task is (Marcora and Staiano 2010), whilst potential motivation is the highest effort a person is willing to exert in order to succeed in a task (Brehm and Self 1989). Hence, when the effort required by an exercise task is perceived to exceed potential motivation, or when perception of effort is so extreme that continuing the task seems impossible, the person consciously decides to stop exercising, or reduces their work output to match or sit below their level of motivation. According to this effort-based decision-making model, any factor that influences RPE and/or potential motivation influences endurance performance, even when the physiological capacity to perform endurance exercise is unchanged. The Psychobiological Model also extends to describe the regulation of closed-loop exercise tasks such as a time trial. During a task in which the individual determines their own pace, regulation of speed or power output is said to be based on not only RPE and motivation, but also three additional factors including knowledge of the distance to cover, knowledge of the distance covered/remaining and previous memory or experience of a similar perception of effort (Marcora 2010).

The Psychobiological Model has been used to provide a valid explanation for the negative impact of mental fatigue on performance during both constant-load time to exhaustion tasks (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013) and self-paced time trials (Pageaux, Lepers et al. 2014, Smith, Marcora et al. 2014). During a time to exhaustion task, RPE increases at a similar rate in both a mentally fatigued and a non-mentally fatigued participant (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013). However, given mental fatigue increases RPE, mentally fatigued participants reach their maximal level of perceived exertion and disengage from the task earlier than in a control condition (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013). During a time trial, knowledge of the distance to cover, knowledge of the distance covered or remaining and experience exercising at a given perceived exertion also play a role in effort regulation. Within mental fatigue research, these additional three factors are kept consistent between mental fatigue and control trials; therefore, it is likely that mental fatigue impairs either RPE and/or potential motivation. During time trials, participants down regulate either speed (MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014) or power output (Brownsberger, Edwards et al. 2013) to maintain a sustainable perceived exertion, with no effect on the overall pacing strategy. When RPE is increased, not finishing the time trial is a more negative outcome than completing the time trial in a longer time, therefore reducing the average speed or power output is believed the most appropriate behavioural response. Although this model sufficiently describes how mental fatigue impairs subsequent endurance performance, the mechanism by which mental fatigue increases RPE is still unclear. Furthermore, this model does not adequately explain the lack of an effect of mental fatigue on maximal and anaerobic exercise tasks.

Strength Model of Self-Control

The Strength Model of Self-Control has also been used by authors to explain the worse endurance performance of individuals following prolonged mental exertion. The model proposes that acts of self-control or self-regulation, draw on some limited resource, akin to a strength or energy, and that one act of self-control will have a detrimental impact on subsequent acts of self-control (Baumeister, Bratslavsky et al. 1998). In this model, self-regulation is viewed as analogous to a muscle. Just as a muscle requires strength and energy to exert force over a period of time, acts that have high self-regulatory demands also require strength and energy to perform. Similarly, as muscles become fatigued after a period of sustained exertion and have reduced capacity to exert further force, self-regulation can also become depleted when demands are made of self-regulatory resources over a period of time (Hagger, Wood et al. 2010). Furthermore, once a person's self-regulatory reserves have been depleted, the resulting diminished self-regulation can be counteracted by replenishing the resource through rest or relaxation (Tyler and Burns 2008) or by taking on fuel (Gailliot, Baumeister et al. 2007). The state of diminished self-regulation has also been termed 'ego-depletion' (Baumeister, Bratslavsky et al. 1998). Self-regulation refers to the capacity for altering one's own responses, especially to bring them into line with standards such as ideals, values, morals, and social expectations, and to support the pursuit of long-term goals (Baumeister, Vohs et al. 2007). Self-regulation enables a person to restrain or override one response, thereby making a different response possible. Stamina is also counted as a measure of self-regulation because it involves resisting fatigue and overriding the urge to quit (Baumeister, Vohs et al. 2007).

There are many examples to which the Strength Model may apply. For example, a thought control task where participants were asked to refrain from thinking about a white bear, reduced persistence on a subsequent anagram task (Muraven, Tice et al. 1998). Supressing emotion while watching an evocative video reduced hand grip time to exhaustion versus controls that were able to freely express their emotions (Muraven, Tice et al. 1998). While completing a mentally fatiguing cognitive task has reduced time to exhaustion during a cycling and an isometric leg extension (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013), impaired running time trial performance (MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014) and negatively affected perceptual motor skills (Duncan, Fowler et al. 2015). Across domains, self-regulation resource depletion has also been shown to coincide with increased subjective effort and fatigue (Hagger, Wood et al. 2010).

In search for physiological mechanisms for ego-depletion, the Strength Model has been extended to suggest that the source of self-regulatory energy is glucose (Gailliot, Baumeister et al. 2007). Acts of self-regulation require increased cerebral functioning, and are likely to cause a concomitant rise in the demand for glucose in the brain (Green, Elliman et al. 1997). On occasions engaging in tasks of self-regulation coincide with reductions in blood glucose levels, which in turn predict poor self-control on behavioural tasks (Benton, Owens et al. 1994) and drinking a glass of lemonade sweetened with sugar helped counteract these effects (Gailliot, Baumeister et al. 2007). Lemonade sweetened with artificial sweeteners and no glucose had no such empowering effect (DeWall, Baumeister et al. 2008, Masicampo and Baumeister 2008, Gailliot, Peruche et al. 2009). Glucose supplementation has also improved running (Nicholas, Williams et al. 1995, Tsintzas, Williams et al. 1996) and walking (Ivy, Miller et al. 1982) endurance capacity, cycling to exhaustion in the heat (Carter, Jeukendrup et al. 2003) and improved mean power output during a simulated cycling time trial (El-Sayed, Balmer et al. 1997). This area of research therefore presents an attractive mechanism for impaired endurance performance with mental fatigue; however, just like the Psychobiological Model, the Strength Model is unable to explain the difference in impact of mental fatigue on different types of exercise performance.

2.11 Implications of Mental Fatigue outside the Laboratory

Occupational

Although much of the literature described in this review has a focus on traditional exercise performance, the implications of mental fatigue are none more important than when looking in an occupational setting. There are many occupational contexts in which attention must be sustained for prolonged periods of time and complex decision making or strategizing is required. In addition, many occupations also involve an aspect of physical performance, and often that physical performance must also be sustained for long periods of time. Soldiers in the defence forces are a prime example of an occupation which demands upmost physical and mental efforts and one where decrements in performance with mental fatigue can have dire consequences. Mental fatigue can also be induced by intense emotional strain and is likely exacerbated by strenuous and/or prolonged physical exertion, inadequate food and water intake and disrupted and lost sleep (Murphy 2002). In the case of a soldier, outcomes of mental fatigue have been associated with preventable non-combat casualties, irrational decision-making and operational failure (Murphy 2002). Similar consequences of mental fatigue may be observed in the emergency service industry, including policeman, fireman, and paramedics. Each of these professions often undertake demanding cognitive work for prolonged periods of time, followed by the need for physical performance.

The long haul transportation industry is another occupational setting which is likely to be affected by mental fatigue. Although driving a truck or train, or piloting a plane may not require a high level of physical effort, high levels of attention and skill must be maintained to ensure a safe arrival. The increased reaction time associated with ensuing mental fatigue has great potential to cause serious damage in this scenario, and therefore greater knowledge of the causes of mental fatigue and any potential mechanisms to lessen, or tolerate greater mental fatigue would be important for this type of setting.

Professional Sport

Professional athletes are highly unlikely to undertake a Stroop task or a similar cognitively demanding task prior to important competition; however, there are many ways in which mental fatigue may influence the performance of professional sports people. Long strategic meetings, scheduling training around part or full time work and looking after a young family are all likely to induce a degree of mental fatigue. Exerting self-regulation is also believed to affect physical performance in a manner similar to that of mental fatigue. Controlling emotions on field or in response to coaches, teammates or the media therefore may impair subsequent endurance performance. Maintaining a strict and restrictive diet and refraining from consuming alcohol, eating junk food or going out with friend may also be mentally effortful for athletes. Likewise, having to behave in a manner that an athlete believes is expected of them, yet may be different to their usual behaviour may also take a mental toll on an athlete. Understanding how mental fatigue may affect the quality of performance and training, managing this fatigue and allowing for recovery from mental fatigue when it is unavoidable may all allow athletes to maximise their performance. Studying the toll of this type of mental fatigue on athletic performance in highly trained athletes is also likely to be more applicable and appealing to coaches and the professional sport industry. Such studies should focus on mental fatigue induced in a natural setting, whether that is during a game, induced by the media or through other avenues.

Brain Endurance Training is another avenue of research that may benefit professional athletes. Brain Endurance Training involves the completion of a cognitively demanding task whilst concurrently completing a physical exercise training program. In an unpublished study, 35 soldiers trained three times per week on stationary cycle ergometers, riding for the same duration and intensity relative to their baseline (Marcora et al. unpublished). In addition to the physical effort, half of the soldiers were also asked to engage in a mentally demanding cognitive task, while they continued to cycle. At the end of the 12-week study, both groups demonstrated comparable increases in maximal oxygen uptake, however, when the soldiers completed a cycling time to exhaustion test at 80% of their respective VO_2max. The group that trained without the mentally demanding task improved their time to exhaustion by an average of 42%, while the soldiers who completed the combined physical and mental training improved their time to exhaustion by an average of 126%. It was suggested that this Brain Endurance Training allowed participants to tolerate a higher perceived effort, so that when the cognitive task was removed or participants completed another task, the remaining task felt less effortful. Although this justification of the results seems reasonable, at the time of this thesis this reference was only available in abstract format, and thus makes it difficult to discuss further. This new technique of training may be beneficial to athletes in a number of ways. Brain Endurance Training may be used as an additional stimulus to further improve the performance of endurance athletes without adding further mechanical toll to the body. Similarly, this mode of training, with a reduced physical component may be used with injured or ill athletes to reduce the effect of detraining when returning to full training and competition. By increasing tolerance to effort, this form of training may also be beneficial for potentially increasing tolerance for other stressful, emotional or mentally fatiguing situations.

Health and Fitness

The implications of mental fatigue are also more far reaching than occupational settings and professional athletes. Mental fatigue does not only impair physical performance but also appears to affect psychological constructs such as motivation, willingness to exert further effort and perception of effort or perceived exertion. The impact of these effects will likely have large implications for those at risk populations who struggle to maintain consistency with their physical activity or exercise levels. A greater understanding of why individuals may feel less motivated to exercise following a day at work, or why a run may seem harder having had a tough or stressful day may encourage individuals to stick with their physical activity program rather than forgoing it. Acknowledging that the exercise may 'feel' harder or that they are less motivated, yet physiologically unchanged may allow for the ability to work past these perceptions. A change as simple as exercising first thing in the morning may make exercise feel easier and be more enjoyable, and therefore more likely that an individual with continue with it. As mental fatigue appears to most inhibit endurance performance, aerobic exercise could be completed in the morning, while resistance or anaerobic training at night may gain more benefit. Furthermore, although the area needs more research, the consumption of caffeine prior to training in a mentally fatigued state may reverse some of the detrimental effects observed with mental fatigue.

Although not fully discussed in this review, completing a cognitive task is described as synonymous with completing a task of self-regulation. The impaired physical performance observed with mental fatigue is therefore similar to performance of a task requiring self-regulation in a state of ego-depletion. In this sense, if we can determine the mechanism for reduced self-regulation, monitor and even train self-regulation, the negative effects of ego-depletion and mental fatigue may be minimised. Practise of self-regulation may help in the rehabilitation of those with deficits in self-control leading to infidelity, alcohol or drug abuse, gambling problems or obesity. The broader knowledge obtained in the studies of mental fatigue may certainly have far and wide reaching consequences.

2.12 Summary

A wealth of research has described the negative impact of mental fatigue on cognitive performance. More recently we have learned that subsequent physical performance may also be impaired by mental fatigue. Research investigating the effect of mental fatigue on physical performance has primarily focussed on prolonged and submaximal endurance exercise, using tasks such as time to exhaustion and time trials. Cardiovascular, metabolic and neuromuscular variables of physical performance are reported to be unaffected by mental fatigue. Rather, mental fatigue appears to increase perception of effort during subsequent endurance performance and thus mentally fatigued participants down-regulate their effort, or disengage from the exercise task earlier than performance in a non-fatigued state.

At the time that this thesis began, no research had been conducted using exercise tasks of short duration and maximal intensity, in addition, the exercise tasks examined within the literature, had very little applicability to any real life sporting or exercise scenario. This initial research was of vital importance to establish the effect of mental fatigue on physical performance, as well as elucidate potential mechanisms behind the effect. However, conducting future research with a more practical application, and valid performance measures are of high importance. Similarly, it is also important to focus on the participant population when examining the effect of mental fatigue on performance. Within an exercise and sport science setting, it is known that different populations can respond differently to the same stimulus, as well as there being variability within the same population. It is important to not only be task specific when examining the effect of mental fatigue on performance, but also participant specific.

Finally, it is unclear what the exact mechanism behind the negative effect of mental fatigue on endurance performance. Although it appears that impaired performance can be attributed to an increase in RPE during endurance exercise, how mental fatigue increases RPE is unknown. Both the Psychobiological Model and the Strength Model of Self-Control have been used to describe the effect of mental fatigue on endurance performance, however, neither of these models can explain why some aspects of physical performance are affected while others are not. Elucidating exactly how mental fatigue affects physical performance will not only increase general knowledge but may also allow for an intervention to be designed to minimise or reverse the effect of mental fatigue on physical performance or to increase tolerance. Such knowledge would benefit not only professional athletes, but those implementing every day health and fitness programs and also a wide range of occupations in which optimal physical and cognitive performance is critical.

Chapter Three: Mental Fatigue Does Not Affect Maximal Anaerobic Exercise Performance

Form E: Declaration of Co-Authored Publication Chapter

In the case of Chapter Three, Kristy Martin contributed to the study design, data collection, statistical analysis and preparation of the manuscript, the extent of this contribution was 70%.

The following co-authors also contributed to the work; Ben Rattray (study design, data collection, preparation of manuscript), Kevin Thompson (study design, preparation of manuscript), Richard Keegan (study design, preparation of manuscript) and Nick Ball (study design, preparation of manuscript). None of the co-authors are students.

Candidate's signature ____________________________ **Date** ____________________

Declaration by co-authors

The undersigned hereby certify that:

1. The above declaration correctly reflects the nature and extent of the candidate's contribution to this work, and the nature of the contribution of each of the co-authors

2. They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise

3. They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication

4. There are no other authors of the publication per these criteria

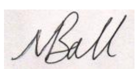
5. Potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit

6. The original data is stored at the University of Canberra Research Institute for Sport and Exercise and will be held for at least five years

Ben Rattray  **Date:** 09·11·2016

Kevin Thompson  **Date:** 09·11·2016

Richard Keegan  **Date:** 09·11·2016

Nick Ball  **Date:** 09·11·2016

3.1 Foreword

The following chapter is the first of three original studies which aim to extend our current knowledge of the impact of mental fatigue on subsequent physical performance. Research completed up until this point had focused largely on endurance exercise tasks, utilising time trials and tests of time to exhaustion. This study focusses on short-duration and maximal intensity exercise tasks, as crucial components of many team sports and competitive events. Twelve team-sport athletes completed a mentally fatiguing and control task in a randomised, double-blind crossover design. Participants were then tested on their ability to complete a maximal isometric leg strength test, a countermovement vertical jump and 3 minute cycling test of anaerobic capacity. This chapter discusses the differences in the effect of mental fatigue between prolonged endurance exercise tasks and maximal anaerobic exercise tasks. This study has been accepted for publication and was first published online in November 2014.

Martin, K., Thompson, K. G., Keegan, R., Ball, N. & Rattray, B. (2014). Mental Fatigue Does Not Affect Maximal Anaerobic Exercise Performance. *European Journal of Applied Physiology*, 115(4), 715-725.

3.2 Abstract

Purpose: Mental fatigue can negatively impact on submaximal endurance exercise and has been attributed to changes in perceived exertion rather than changes in physiological variables. The impact of mental fatigue on maximal anaerobic performance is, however, unclear. Therefore, the aim of the present study was to induce a state of mental fatigue to examine the effects on performance, physiological and perceptual variables from subsequent tests of power, strength and anaerobic capacity.

Methods: Twelve participants took part in the single-blind, randomised, crossover design study. Mental fatigue was induced by 90 min of the computer-based Continuous Performance Task AX version. Control treatment consisted of 90 min of watching emotionally neutral documentaries. Participants consequently completed countermovement jump, isometric leg extension and a 3-min all-out cycling tests.

Results: Results of repeated measures analysis of variance and paired t tests revealed no difference in any performance or physiological variable. Rating of perceived exertion tended to be greater when mentally fatigued (mental fatigue = 19 ± 1 vs control = 18 ± 1, $p = 0.096$, $\eta^2p = .232$) and intrinsic motivation reduced (mental fatigue = 11 ± 4 vs control = 13 ± 6, $p = 0.063$, $d = 0.597$) in the mental fatigue condition.

Conclusions: Near identical responses in performance and physiological parameters between mental fatigue and control conditions suggest that peripheral mechanisms primarily regulate maximal anaerobic exercise. Whereas mental fatigue can negatively impact submaximal endurance exercise, it appears that explosive power, voluntary maximal strength and anaerobic work capacity are unaffected.

Mental Fatigue Does Not Affect Maximal Anaerobic Exercise Performance

3.3 Introduction

Mental fatigue is a change in psychobiological state, caused by prolonged periods of demanding cognitive activity (Marcora, Staiano et al. 2009). This change is gradual and cumulative and has subjective and objective manifestations including increased resistance against further effort (Meijman 2000), changes in mood (Holding 1983) and feelings of 'tiredness' and 'lack of energy'. Mental fatigue can be brought about by sustained performance of a single cognitive task but can also include different tasks that require mental effort, such as work related fatigue. It is well known that mental fatigue negatively affects cognitive performance (van der Linden, Frese et al. 2003, Boksem, Meijman et al. 2005, Boksem and Tops 2008); however, only recently has it been observed that mental fatigue impacts on subsequent exercise performance (Marcora, Staiano et al. 2009, Brownsberger, Edwards et al. 2013, Pageaux, Marcora et al. 2013, Pageaux, Lepers et al. 2014). For example, mental fatigue reduced time to exhaustion during both high-intensity (80 % of peak power output) cycling (Marcora, Staiano et al. 2009) and a prolonged isometric leg extension (target torque of 20 % maximal voluntary contraction)(Pageaux, Marcora et al. 2013). Average running speed was decreased in a 5-km time trial (Pageaux, Lepers et al. 2014) and mental fatigue lowered self-regulated power output during ergometer cycling, when participants were instructed to sustain effort corresponding to descriptors from Borg's 6–20 Rating of Perceived Exertion (RPE) (Borg 1982) scale of fairly light (RPE of 11) and hard (RPE of 15) (Brownsberger, Edwards et al. 2013).

Despite the relatively consistent observation that mental fatigue impairs subsequent endurance performance, the mechanism behind this effect is presently unknown. Previous studies have revealed no difference in any physiological variable between mental fatigue and control conditions. Variables that were previously thought to limit exercise performance, for example heart rate, cardiac output, oxygen consumption or lactate during cycling to exhaustion (Marcora, Staiano et al. 2009), neuromuscular function during a prolonged isometric leg extension (Pageaux, Marcora et al. 2013) and pacing strategy in a 5-km running time trial (Pageaux, Lepers et al. 2014) were unaffected by mental fatigue. Despite the lack of physiological differences between conditions, poorer performances were observed in the experimental trial. Subsequently the negative impact of mental fatigue on performance has been attributed to the greater perceived exertion experienced by participants when mentally fatigued (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, Pageaux, Lepers et al. 2014). Prolonged mental exertion is hypothesised to directly affect the cortical centres involved in the cognitive aspect of central motor command (Hallett 2007) and the primary sensory input for perceived exertion (Marcora, Staiano et al. 2009). Specifically, the anterior cingulate cortex (ACC), an area of the prefrontal cortex strongly activated by tasks requiring cognitive effort (Paus, Koski et al. 1998), is believed to be affected by mental fatigue. The ACC has shown correlation between changes in activation and changes in RPE during manipulations of exercise intensity under hypnosis and motor imagery (Williamson, McColl et al. 2001, Williamson, McColl et al. 2002, Williamson, Fadel et al. 2006), and rats with experimental ACC lesions engage significantly less than normal rats in tasks requiring physical effort to obtain a larger reward (Walton, Bennerman et al. 2003, Rudebeck, Walton et al. 2006, Walton, Kennerley et al. 2006). Furthermore, experimental evidence from in vitro and animal studies suggest that neural activity increases extracellular concentrations of adenosine (Lovatt, Xu et al. 2012) and that brain adenosine induces a reduction in endurance performance (Davis, Zhao et al. 2003).

While the effect of mental fatigue on endurance performance appears clear, the impact on maximal anaerobic exercise performance is unknown. Rozand et al. (Rozand, Lebon et al. 2014) observed no change in maximal muscle activation or isometric elbow flexion torque following either a mental training session (using imagined maximal isometric elbow flexion contractions), or a combined physical and mental training session (using both imagined and actual maximal contractions). No change in performance occurred despite greater perceived mental fatigue in the mental training sessions, relative to the physical session alone. In contrast, Bray et al. (Bray, Graham et al. 2012) observed a linear decrease in force production during 4 s maximal voluntary handgrip contractions, when completed intermittently between 3 min of an incongruent Stroop task. However, the study of Bray et al. (Bray, Graham et al. 2012) consisted of a number of methodological flaws that may account for the differences in observations. For example, in the central fatigue review by Gandevia (Gandevia 2001), a number of guidelines were provided to ensure participants exerted a true maximal effort during maximal voluntary contractions. Among the guidelines was the use of visual feedback to maximise voluntary effort. Feedback was not provided by Bray et al. (Bray, Graham et al. 2012). Furthermore, Rozand et al. (Rozand, Pageaux et al. 2014) demonstrated that completion of a modified incongruent Stroop task did not affect maximal force capacity of the knee extensors when completed intermittently between the cognitive tasks. Where maximal anaerobic tasks are predominantly regulated by peripheral fatigue such as availability of metabolic substrates (Coggan and Coyle 1991), accumulation of metabolites (Fitts and Metzger 1993) and impairments in neuromuscular transmission (Balog, Thompson et al. 1994), endurance tasks are additionally altered by central fatigue, a reduction in central motor drive (Amann 2011). Given the differences in mechanisms of fatigue between exercise tasks, it is possible mental fatigue affects these two types of activity differently.

Exercise tasks of short duration and maximal intensity utilizing explosive power, strength and the anaerobic work capacity are of interest as they are critical to many competitive events. For example, high-intensity activity in soccer has been found to be related to the overall success of the team (Rampinini, Coutts et al. 2007, Di Salvo, Gregson et al. 2009), explosive strength training improved 5 km running performance in well-trained endurance athletes (Paavolainen, Häkkinen et al. 1999) and anaerobic power of the leg and arm muscles are believed to determine success in wrestling (Hübner-Wozniak, Kosmol et al. 2004). These sporting events have traditionally been thought to be limited by anaerobic energy depletion, accumulation of metabolic by-products or failure of the muscle fibre contractile mechanisms. Therefore, the aim of the present study was to investigate the impact of prolonged mental exertion leading to mental fatigue, on subsequent maximal anaerobic exercise. Mental exertion consisted of 90 min of a cognitively demanding computer task requiring sustained attention, working memory, response inhibition and error monitoring (Carter, Braver et al. 1998). Explosive power, maximal strength and anaerobic work capacity were assessed using a countermovement jump (CMJ), isometric leg extension and a 3-minute all-out cycling test (3MT). Given previously mental fatigue has not impacted on peripheral mechanisms of fatigue or induced any extent of central fatigue, authors hypothesised that prolonged mental exertion would not impact upon the performance of maximal anaerobic exercise tasks.

3.4 Methods

Participants

Twelve participants (7 men and 5 women; age 23 ± 3 years and peak oxygen uptake 53 ± 13 $l{\cdot}min^{-1}$, gas exchange threshold 2.6 ± 0.7 $l{\cdot}min^{-1}$) gave informed consent, for the study protocol approved by the University of Canberra Committee for Ethics in Human Research. Eligibility included being aged between 18 and 40 years, free from any known disease or injury, a non-smoker and not taking any medication except for contraceptives. All participants were involved in high-intensity training at least three times per week. High-intensity activity included training and competition for field-based team sports or high-intensity interval training included in triathlon training programs. Participants had no history of sleep disorders and were not shift workers. During the experiment participants were naive to the precise aim and hypothesis. Participants were led to believe the study was examining whether watching television or completing a mentally engaging task is good preparation for maximal anaerobic exercise performance. At the end of the final visit, participants were debriefed and asked not to discuss the study with other participants.

Study Design and Procedures

A single-blind, randomised, crossover study design was employed. Testing took place on five occasions. The first testing session consisted of an incremental ramp protocol to determine resistance for the 3MT. The second and third session acted as familiarisation trials. These trials mimicked what occurred in the physical testing portion of the experimental and control trials. During these trials participants were also familiarised with the questionnaires and scales used in subsequent sessions. During the fourth and fifth testing sessions participants completed the Profile of Mood States (POMS) questionnaire prior to completing baseline CMJ and isometric leg extensions. Participants then undertook either the experimental or control trial. Treatment order was randomly allocated per balanced permutations generated by a web-based computer program (http://www.randomization.com). Following the treatment or control sessions, participants completed a post-treatment POMS, Rating Scale of Mental Effort (RSME) and Situational Motivation Scale (SIMS). Participants then completed five minutes of unloaded warm-up on the cycle ergometer followed by supervised static and dynamic stretching of the lower limbs. Cadence was monitored and kept consistent between trials. Three minutes of static stretching was followed by ten leg swings, ten body weight squats and ten lunges. The warm-up was consistent between all tests and trials. Following the warm-up participants completed three CMJ, three maximal isometric leg extensions and the 3MT. A 3-min recovery was allowed between the final CMJ and the leg extension and the leg extension and the 3MT. Testing on all occasions was performed in the same order. A schematic of the study design is represented in Figure 3.1. A single, consistent researcher was present at all testing sessions and provided encouragement at regular intervals during each of the exercise tasks. An effort was made to maintain consistency of the content and delivery of the encouragement.

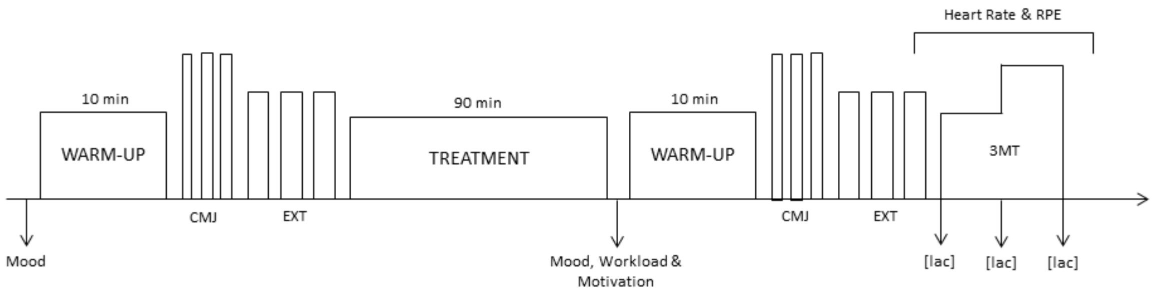


Figure 3.1 Schematic of experimental session three and four. WU warm up, CMJ countermovement jump, EXT isometric leg extension, 3MT 3 min all out cycle test, [Lac] plasma lactate concentration, RPE rating of perceived exertion

Participants were given written instructions to arrive at the laboratory fully hydrated, to have slept for at least 7 h the night before, refrained from the consumption of alcohol, and to have avoided any vigorous exercise 24 h prior to all testing. Participants were also instructed to avoid any caffeine for at least 3 h before testing. Finally, participants were instructed to record their food intake at breakfast and to repeat the recorded intake before the following testing session and to eat at the same time. All testing sessions were conducted at the same time of day, for each individual, on each occasion. Participants completed testing sessions over a period of 5 weeks, with a minimum 48 h recovery between visits. Environmental conditions in the laboratory were kept consistent and the same lead researcher was present for all trials. Throughout each session only water was consumed.

Mental Fatigue Treatment

The mental fatigue treatment consisted of 90 min of a modified version of the computer-based Continuous Performance Test AX-version (AX-CPT). A version of this task has been used previously to induce a state of mental fatigue (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013). The current version utilised all letters of the alphabet as distractor letters, opposed to the two distractor letters in the aforementioned task. Continuous performance tests are associated with significant activation of the anterior cingulate cortex (Riccio, Reynolds et al. 2002), an area of the prefrontal cortex affected by mental fatigue (Lorist, Boksem et al. 2005). In this version of the task, letters are visually presented one at a time in a continuous fashion on a computer screen. Participants were instructed to respond with a right mouse press whenever the stimulus included an X that was preceded by an A. The left mouse button was pressed for all other stimuli, including an X that was not preceded by an A, and any other letter. Letter sequences were presented in pseudorandom order, such that 20% of the stimuli were targets (A–X). The remaining letters of the alphabet served as non-targets. All letters were presented centrally in black ink, on a white background for duration of 200 ms each. The inter-trial interval varied across trials and was 1.5, 2 or 2.5 s (including the duration of the stimulus). Inter-trial interval was randomised across the task. Practice trials were allowed and the participant was trained in the correct performance of the test before formal testing was initiated. To further increase engagement and motivation in the AX-CPT, a $50 prize was awarded for the best five performances in terms of both correct detections and reaction time. Because increased reaction time is a well-established effect of mental fatigue (Boksem, Meijman et al. 2005, Marcora, Staiano et al. 2009), the speed and proportion of correct responses to the AX trials during the first and last 15 min period of the AXCPT were compared as a manipulation check.

Control Treatment

Control treatment consisted of watching "World Class Trains—The Venice Simplon Orient Express" and "The History of Ferrari—The Definitive Story" for 90 min on the same computer used for the mental fatigue treatment. The documentaries were chosen based on topics capable of maintaining a neutral mood and stable heart rate (Silvestrini and Gendolla 2007). During both treatments, the lead researcher observed participants throughout the 90 min to ensure compliance.

Physical Performance

An incremental ramped protocol was conducted on a cycle ergometer set in hyperbolic mode (High Performance Ergometer, Schoberer Rad MeBtechnik, Germany) to determine the workload for the

3MT. The ergometer seat and handlebars were adjusted for comfort and participants' own pedals fitted if required. Geometric setup of the ergometer was consistent between tests and trials. The ramp protocol consisted of five minutes of unloaded baseline pedalling, followed by a ramped increase in power output of 30 W per minute until volitional exhaustion. Participants were instructed to maintain their preferred cadence (≈70–100 rpm) for as long as possible. The test was terminated when the pedal rate fell to more than 10 rpm below the chosen cadence for more than 10 s, despite strong verbal encouragement.

Vertical jump performance consisted of a countermovement jump. No attempts were made to standardise the amplitude or rate of the countermovement; rather participants were encouraged to self-select these variables with the view to obtaining maximum jump height. The power, velocity and acceleration variables of the CMJ were recorded using the GymAware optical encoding system (Kinetic, Mitchell, Australia), with the linear position transducer attached to the right side of a wooden dowel rod and placed on the upper portion of the scapula region of the participant's back. The bar maintained contact with the body at this position, by the participant placing their hands on the bar and pulling it into their body. The retraction tension of the linear position transducer was 5 N, which was adjusted for calculating peak power, velocity and acceleration. Displacement time data were sampled at 29 kHz and down sampled to 50 Hz where position points were time stamped when a change in position was detected; with time between samples limited to a minimum of 20 ms. Each participant recovery between each jump. The first two trials were used as warm-up. Participants were instructed to jump as high as possible from a standing start. Only the best jump for each participant was used in data analysis. Eccentric displacement, concentric peak velocity, peak force and mean power were analysed between conditions due to their sensitivity to neuromuscular fatigue (Taylor, Hopkins et al. 2012). Height of the jump was recorded as a performance measure.

Leg strength was assessed by an isometric maximal knee extension of the right leg only using an isokinetic dynamometer (KinCom; Kinetic Communicator, Chattecx, Chattanooga, TN). Participants were seated in a rigid chair and firmly strapped at the hip and distal thigh. The rotational axis of the dynamometer was visually aligned to the lateral femoral epicondyle, and the lower leg was attached to the dynamometer lever arm just above the medial malleolus. The hip, thigh and lower leg were firmly attached to the chair and lever arm, respectively, while the foot was free to move around the ankle joint. The individual positioning for each participant of the seat, backrest, dynamometer head and lever arm length was kept consistent for all testing. The geometric setup of the dynamometer was completed by the same researcher on each occasion. Isometric contractions were performed in a seated position with a 90° flexion angle at both the hip and knee. Following two submaximal warm-up contractions, each participant performed three, 6 s knee extensions at maximal effort. Each 6 s effort was interspersed with 30 s passive recovery. Participants were instructed to contract "as forcefully as possible". Visual feedback of the instantaneous dynamometer force was provided to the participants on a computer screen. Peak and mean torque, time to peak torque and time to half peak torque were recorded.

The 3MT was used to assess anaerobic work capacity. It is a test requiring an initial maximal effort which is then followed by a significant drop-off in power output as the participant experiences significant fatigue. The test requires considerable effort, motivation and commitment by the participant. The test has been used as a method of deriving critical power from a single exercise bout (Vanhatalo, Doust et al. 2007). Critical power represents the highest sustainable work rate (Vanhatalo, Doust et al. 2007), while the maximum amount of work that can be performed above critical power is often referred to as anaerobic work capacity (Morton 2006). The 3MT has also been shown to result in a reproducible power output profile (Burnley, Doust et al. 2006). The test begins with 3 min of unloaded baseline pedalling at a self-selected cadence, this cadence was noted and repeated in subsequent trials, and participants were then asked to increase their cadence during the last five seconds of the baseline period, followed by an all-out 3-min effort. Resistance for the 3MT was derived in accordance with the original investigators' procedures (Burnley, Doust et al. 2006). In brief, the linear mode of the ergometer was used so that participants would attain a power output halfway between their gas exchange threshold and peak oxygen uptake, on reaching their preferred cadence. Gas exchange threshold and peak oxygen uptake were derived from the incremental ramp test. During the 3MT, participants were not aware of the elapsed time to prevent pacing and strong verbal encouragement was provided throughout the test by the same lead researcher. To ensure an all-out effort, participants were instructed to maintain their cadence as high as possible at all times. Mean and peak power values, critical power and anaerobic work capacity were recorded for each trial. Critical power was calculated as the average power output for the final 30 s of the test, and the anaerobic work capacity was calculated as the power–time integral above critical power (Vanhatalo, Doust et al. 2007). Cadence and pacing profiles were established as means over twelve time points.

Physiological Measures

Oxygen uptake during the ramp protocol was recorded using an open-circuit indirect calorimetry system (True-One 2400 Metabolic Measurement System, Parvo Medics, USA). Oxygen uptake was recorded to determine peak oxygen uptake and gas exchange threshold to establish individual workloads for the subsequent 3MT. Peak oxygen uptake was determined as the highest oxygen uptake recorded over a 10-s period. Data was reduced to 10 s averages for the estimation of the gas exchange threshold using the V-slope method (Beaver, Wasserman et al. 1986). Capillary blood samples were collected from a fingertip on the left hand prior to the warm-up of the 3MT, 10 s following termination and 4 min post. Samples were analysed using a lactate analyser (Lactate Pro, Arkay, Japan). These samples were used to compare plasma lactate concentration between treatments and over time. Heart rate was recorded during the incremental ramp test and the 3MT with a heart rate monitor fitted by a chest strap (T34 Non-Coded Heart Rate Transmitter, Polar, Finland). Heart rate was recorded every minute during the incremental ramped test and every 30 s during the 3MT.

Perceptual Measures

Mood states were assessed using the POMS inventory. The POMS inventory contains 65 adjectives rated on a five-point scale (0 = not at all, 4 = extremely) designed to measure tension, depression, anger, vigour, fatigue and confusion, as well as provide a global mood state score (McNair, Lorr et al. 1985). POMS has been well established in terms of validity and reliability (McNair, Lorr et al. 1985) and is used widely in research with clinical and normal populations, including in the exercise domain (Snow and LeUnes 1994). The subscales of fatigue and vigour were of particular interest in this study.

The RSME was used to measure the subjective mental workload of each treatment (Zijlstra 1993). The RSME was presented as a single continuum on a sheet of paper with validated reference points along the scale. Participants were asked to mark on the vertical line, how much cognitive effort they had to invest in the task, within the scale anchored by written indicators of ‘not at all effortful’ to ‘very effortful’. The distance of the mark from the baseline was measured in millimetres. This single-dimension scale has good sensitivity to mental workload (Verwy and Veltman 1996).

The SIMS was used to assess participants’ motivation towards the upcoming physical tasks (Guay, Vallerand et al. 2000). The SIMS is a 16-item self-report inventory, which is designed to measure intrinsic motivation, identified regulation, external regulation and amotivation. Intrinsically motivated behaviours are those that are engaged in for the pleasure and satisfaction derived from performing them (Deci 1971). Identified regulation occurs when behaviour is valued and perceived as being chosen by oneself; however, the motivation is still extrinsic because the activity is not performed for itself but as a means to an end (Guay, Vallerand et al. 2000). External regulation occurs when behaviour is regulated by rewards or to avoid negative consequences (Guay, Vallerand et al. 2000). Extrinsic motivation pertains to a wide variety of behaviours where the goals of action extend beyond those inherent in the activity itself (Guay, Vallerand et al. 2000). Each item was rated on a 7-point Likert scale (1 = corresponds not at all, 7 = corresponds exactly). Scores were calculated for each individual subscale. Reliability and construct validity have been established for the SIMS and found suitable for both field and laboratory settings (Standage, Duda et al. 2003).

Perceived exertion during the 3MT was assessed using the Borg 6–20 scale (Borg 1970). The term perceived exertion was defined as a subjective rating of exertion, based on the physical sensations a person experiences during exercise. Participants were instructed to rate whole body perceived exertion at the midway point of the warm-up and during the last 15 s of each minute of the 3MT. Perceived exertion was rated on a large scale placed in front of participants at the appropriate time point. Each participant was instructed to rate the overall sensation of how strenuous the exercise was, with no attempt made to distinguish between sensations such as pain, effort and discomfort. A rating of 6 was to correspond to sensations associated with being at rest and a rating of 20 as sensations experienced with the hardest exercise participants had ever completed. Participants were further requested to 'not think too much', and to pick the number on the scale which best described how they felt. Administration of all of the scales was completed in the same order on each occasion.

Statistical Analysis

All data are presented as mean ± standard deviation. Paired t tests were used to assess the effect of condition (mental fatigue vs control) on 3MT performance measures, subjective workload and motivation. A paired t test was also used to compare the proportion of correct detections and reaction time between the first and last 15 min of the AX-CPT. Repeated measures analysis of variance (ANOVA) were used to assess the effect of condition and time using two time points for mood, CMJ and leg extension variables, three time points for lactate concentration, four time points for RPE, eight time points for heart rate and twelve time points for cadence and pacing profiles. When the sphericity assumption was violated, the Greenhouse-Geisser correction was employed. Significance was set at 0.05 (2-tailed) for all analyses. Effect size for paired t tests were calculated as Cohen's d, using the small = 0.2, medium = 0.5 and large = 0.8 interpretation (Cohen 1992). Effect size for each repeated measures ANOVAs were calculated as partial eta squared (η^2p), using the small = 0.02, medium = 0.13 and large = 0.26 interpretation (Bakeman 2005).

3.5 Results

Mental Fatigue

The proportion of correct detections was not different from the first to the last 15 min of the mental fatigue treatment ($p = 0.152$, $d = 0.445$). Reaction time tended to increase from the beginning to the end of the AX-CPT although not significant (from 484 ± 81 to 511 ± 99 ms, $p = 0.095$, $d = 0.527$). Cognitive effort was rated as greater following the AX-CPT, relative to control (Mental fatigue, MF = 71.7 ± 18.7 vs. Control, CON = 26.0 ± 23.1, $p < 0.001$, $d = 1.994$). Vigour decreased and fatigue increased over time in both conditions (Vigour: $p < 0.001$, 2p = 0.794 and Fatigue: $p = 0.015$, η^2p = 0.431) but there was no condition or interaction effect (Vigour: $p = 0.970$, 2 p < 0.001 and $p = 0.385$, $\eta^2p = 0.069$ and Fatigue: $p = 0.385$, $\eta^2p = 0.069$ and $p = 0.358$, $\eta^2p = 0.077$).

Physical Performance

There was no difference between conditions during the 3MT for peak power (MF = 689 ± 298 vs CON = 700 ± 301 W, $p = 0.412$, $d = 0.246$), mean power (MF = 298 ± 79 vs CON = 294 ± 77 W, $p = 0.217$, $d = 0.378$), critical power (MF = 238 ± 55 vs CON = 242 ± 64 W, $p = 0.537$, $d = 0.184$) or estimated anaerobic work capacity (MF = 9.4 ± 5.9 vs CON = 8.0 ± 2.9 kJ, $p = 0.315$, $d = 0.304$). The group mean responses to the 3MT are shown in Figure 3.2. When the time data were expressed as 15 s averages and compared, cadence was not different between conditions ($p = 0.176$, $\eta^2p = 0.711$), but there was a main effect of time ($p < 0.001$, $\eta^2p = 0.159$). Specifically cadence was significantly reduced from each 15 s time bin from 45 to 120 s. Power output was also not different between conditions ($p = 0.195$, $\eta^2p = 0.147$), but showed a main effect for time ($p = 0.001$, $\eta^2p = 0.634$). Power output was reduced from 15 to 75 s. There was no interaction effect for cadence or power output. Similarly, there was no difference for any recorded variable pre to post treatment or between conditions during the CMJ or isometric leg extension (Table 3.1).

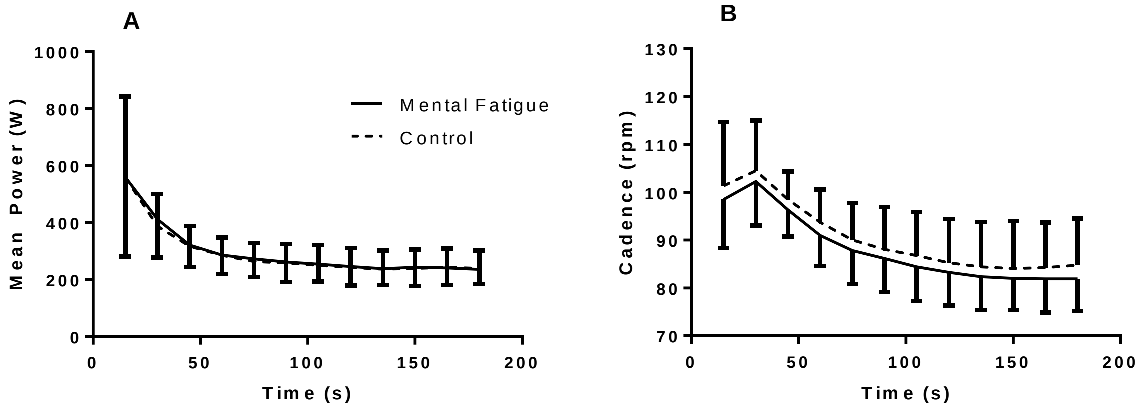


Figure 3.2 Mean power output profile (a) and time course of cadence (b) for mental fatigue and control condition. Data is presented as mean ± SD

Variable	CON-PRE	CON-POST	MF-PRE	MF-POST
Countermovement Jump				
Mean Power (W)	2537 ± 920	2566 ± 1001	2558 ± 979	2647 ± 957
Peak Force (N)	2041 ± 542	1977 ± 539	2071 ± 563	2051 ± 683
Concentric Peak Velocity (m.s^{-1})	3.06 ± 0.43	3.07 ± 0.48	3.08 ± 0.47	3.13 ± 0.53
Eccentric Displacement (m)	0.51 ± 0.12	0.52 ± 0.48	0.52 ± 0.12	0.54 ± 0.13
Jump Height (m)	0.40 ± 0.09	0.39 ± 0.09	0.41 ± 0.07	0.39 ± 0.08
Isometric Leg Extension				
Peak Torque (Nm)	244 ± 61	248 ± 41	239 ± 81	249 ± 87
Mean Torque (Nm)	216 ± 55	223 ± 41	215 ± 76	223 ± 81
Time to Half Peak Torque (s)	0.32 ± 0.27	0.35 ± 0.18	0.32 ± 0.26	0.36 ± 0.23
Time to Peak Torque (s)	3.08 ± 1.12	2.96 ± 0.99	2.75 ± 1.26	2.62 ± 0.83
Peak Torque Slope (Nm.s^{-1})	173 ± 86	147 ± 78	168 ± 116	224 ± 80

Table 3.1 Change in countermovement jump and isometric leg extension variables from baseline (PRE) to post treatment (POST), and between conditions. No variable was significantly different between time points or conditions

Physiological Measures

Heart rate and lactate concentration increased over time (HR: $p < 0.001$, $\eta^2p = 0.948$ and Lactate: $p < 0.001$, $\eta^2p = 0.959$), but there was no condition or interaction effect (HR: $p = 0.441$, $\eta^2p = 0.055$ and $p = 0.350$, $\eta^2p = 0.089$ and Lactate: $p = 0.847$, $\eta^2p = 0.004$ and $p = 0.980$, $\eta^2p = 0.002$).

Perceptual Measures

Identified regulation (MF = 14 ± 5 vs CON = 16 ± 5, $p = 0.201$, $d = 0.392$), external regulation (MF = 10 ± 8 vs CON = 10 ± 8, $p = 0.809$, $d = 0.072$) and amotivation (MF = 8 ± 4 vs CON = 6 ± 2, $p = 0.222$, $d = 0.374$) were not different between conditions as determined by the SIMS. Intrinsic motivation tended to be reduced following the mental fatigue treatment, with a medium effect size (MF = 11 ± 4 vs. CON = 13 ± 6, $p = 0.063$, $d = 0.597$). The effect of mental fatigue on motivation is represented in Figure 3.3. RPE increased over time in both conditions. Perceived exertion increased over time ($p<.001$, $\eta^2p = 0.928$) and although not significant, RPE tended to be greater when mentally fatigued, evidenced by the medium effect size (MF = 19 ± 1 vs CON = 18 ± 1, $p = 0.096$, $\eta^2p = 0.232$) (Figure 3.4). There was no significant interaction effect between condition and time ($p = 0.803$, $\eta^2p = 0.20$).

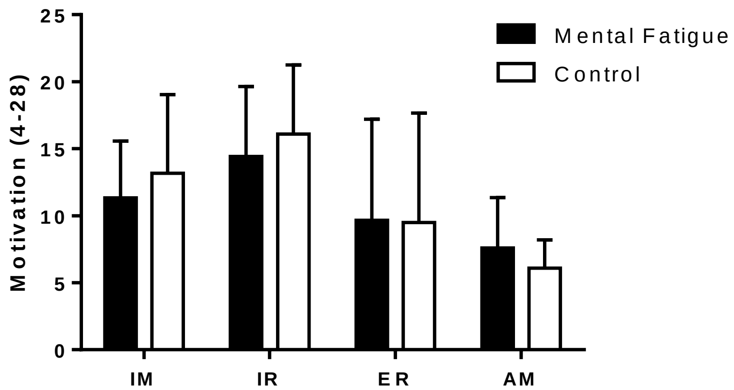


Figure 3.3 Effect of condition on motivation. IM - intrinsic motivation, IR - internal regulation, ER - external regulation, AM - amotivation. Data is presented as mean ± SD

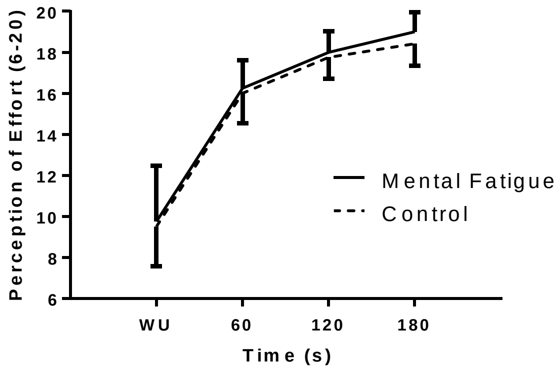


Figure 3.4 Effect of mental fatigue on perception of effort during 3MT. Data is presented as mean ± SD

3.6 Discussion

The primary finding of the present study was that a state of induced mental fatigue did not affect the performance of maximal anaerobic exercise tasks. Physiological variables remained unchanged between experimental and control conditions, and despite a tendency for RPE to be greater and a tendency for intrinsic motivation to be reduced following the AX-CPT, measures of explosive power, voluntary maximal strength and anaerobic work capacity were not affected. Ninety minutes of the AX-CPT was successful in inducing a state of mental fatigue. This was evidenced by the trend for increased reaction time and greater rating of mental effort, compared to control.

None of the 3MT performance variables were different between mental fatigue and control conditions. The power output profile and the time course of cadence were near identical in both trials, suggesting central motor drive was unaffected by mental fatigue. Similarly, the lack of difference in estimates of critical power and anaerobic work capacity indicate that the energy contribution during the experimental condition was also unaffected by mental fatigue. From the outset of the 3MT (0–10 s), all participants produced peak power outputs followed by a consistent decline in performance before levelling off during the final 30 s. The comparable all-out pacing profile and inability to maintain force, the near maximal heart rate and RPE values, as well as the elevated plasma lactate concentration suggest maximal efforts were achieved on both occasions.

Performance during a CMJ and an isometric leg extension were also unaffected by mental fatigue. Countermovement jumps have been used previously to assess neuromuscular fatigue in athletes with the measures of eccentric displacement, mean power and peak velocity force during the concentric portion being notably sensitive to fatigue (Taylor, Hopkins et al. 2012). The present study, however, found no difference in any of these variables when mental fatigue was induced through prior mental exertion. Similarly, and consistent with the present findings, mental fatigue was reported to not induce changes in neuromuscular function of the knee extensor muscles (Pageaux, Marcora et al. 2013, Rozand, Pageaux et al. 2014) or elbow flexors (Rozand, Lebon et al. 2014). In all of these studies, however, muscle function was assessed using a single joint, isometric movement. Early researchers for instance suggested that among the processes affected by mental fatigue, is the coordination and accurate timing of tasks (Bartlett 1943). Mental fatigue does not seem to affect maximum strength (Bray, Martin Ginis et al. 2008, Pageaux, Marcora et al. 2013); however, it has been observed that mental exertion has an effect on the electromyography (EMG) activation required to generate and sustain a submaximal force (Bray, Martin Ginis et al. 2008). Taken individually an increase in EMG activation may represent an increase in motor unit recruitment to carry out a movement. Several muscles, however, contribute to the production of an action, and when individual muscles are analysed, it cannot be determined whether an increase in EMG activation is representative of an increase in activation of the total muscle group or whether the increase of motor unit recruitment of one muscle is to supplement decreased activation of another. Individual muscles within a muscle group co-contract to stabilise a joint and create an efficient movement pattern (Ford, van den Bogert et al. 2008). It is possible therefore, that if participants were required to complete a more complex, dynamic movement, mental fatigue may impact upon performance. The results of the present study, however, suggest no effect of mental fatigue on either a CMJ or knee extensor, isometric maximal strength test.

The disparity between the impact of mental fatigue on submaximal endurance exercise and maximal anaerobic exercise may lie in the performance characteristics of each task. Submaximal endurance exercise can be limited central fatigue, a progressive reduction in voluntary activation of muscle during exercise (Gandevia 2001), as well as altered by peripheral fatigue, fatigue produced by changes at or distal to the neuromuscular junction (Gandevia 2001). In contrast, during one-off maximal anaerobic tasks, peripheral fatigue plays the primary modulating role. Pacing is defined as the efficient use of energetic resources during athletic competition, so that all available energy stores are used before finishing a race, but not so far from the end of a race that a meaningful slowdown can occur (Foster, de Koning et al. 2003). It has been suggested that pacing is regulated by the brain for prolonged endurance exercise (Noakes 2012), while short-duration maximal anaerobic tasks are less influenced by pacing strategy than metabolic fatigue. Although pacing strategy is still important for short-duration tasks, this usually only occurs when the initial power output is lower than is possible if the athlete is instructed to perform an all-out effort with no regard for overall performance (Nummela, Vuorimaa et al. 1992). As instructed, participants during the 3MT adopted an all-out approach, accelerating to peak power quickly and gradually decreasing power output with increasing duration. All-out pacing is characterised by the athlete working maximally from the start of the event and rapidly fatiguing as a result (Thompson 2014). With a reduced cognitive component of the exercise task, mental fatigue may influence performance less.

An increase in RPE has been observed consistently, and to a larger extent, in other studies where mentally fatigued participants completed exercise tasks of a longer duration and lower intensity than the 3MT (Marcora, Staiano et al. 2009, Brownsberger, Edwards et al. 2013, Pageaux, Lepers et al. 2014). In the present study, RPE tended to be greater when mentally fatigued; however, this difference did not reach significance, nor did increased RPE impact on performance measures. Although the mechanisms behind the increase in perception of effort have yet to be fully elucidated, mental fatigue is believed to act on the anterior cingulate cortex (ACC), an area of the prefrontal cortex associated with error detection (Carter, Braver et al. 1998), decision making (Walton, Kennerley et al. 2006) and perception of effort during exercise (Williamson, McColl et al. 2001, Williamson, McColl et al. 2002, Williamson, Fadel et al. 2006). During endurance exercise, RPE rises as a linear function of duration, reaching a maximum value at the termination of a maximal effort (Noakes 2012). During the 3MT the RPE response was curvilinear in nature with a rapid increase evident following the first minute when participants were attempting to maintain peak power output (unsuccessfully) in the face of rapidly developing fatigue. Whereas RPE during submaximal endurance exercise may indicate pacing strategy or exercise duration remaining (Crewe, Tucker et al. 2008), the use of RPE during short-duration and maximal exercise tasks is less clear.

In the present study, intrinsic motivation tended to be reduced when mentally fatigued, despite no change in performance. In considering the issue of quantifying motivation, the present study suggests that intrinsic motivation, but not other forms of motivation, may be reduced when mentally fatigued. In the absence of changes in physiological variables, this may suggest an integral role for intrinsic motivation in determining how performers respond to mental fatigue. Accordingly, intrinsic motivation is suggested as one key mechanism through which the effects of mental fatigue may be generated. Further, if supported, this finding would warrant serious attention when considering how to 'motivate' participants in fatigue and pacing studies, as cash prizes and normative comparisons have consistently been shown to undermine intrinsic motivation (Deci 1971, Deci 1972, Vansteenkiste and Deci 2003). A number of previous studies have found no difference in motivation between mental fatigue and control conditions (Marcora, Staiano et al. 2009, Brownsberger, Edwards et al. 2013, Pageaux, Marcora et al. 2013, Pageaux, Lepers et al. 2014). Limitations of previous research, however, include measuring motivation as a single unit and not differentiating between types of motivation (Marcora, Staiano et al. 2009, Brownsberger, Edwards et al. 2013). By quantifying motivation in this simplified way, it is possible that any impact of mental fatigue on intrinsic motivation may have been concealed. Furthermore, motivation has been modified in previous studies, using external incentives to enhance performance of the physical tasks (Marcora, Staiano et al. 2009, Pageaux, Lepers et al. 2014). The results of the present study, however, suggest that it might be peripheral fatigue and types of motivation other than intrinsic motivation which modulated the 3MT exercise performance. Given the medium effect size of the change in perceptual measures, and no effect of mental fatigue on exercise performance, we suspect that under the conditions of the present study there are not likely to be any practical applications leading to changes in current behaviour. Future research should focus more closely on change in intrinsic motivation with mental fatigue.

3.7 Conclusion

Despite successfully inducing a state of mental fatigue, 90 min of the AX-CPT did not have any impact on the performance of a CMJ, a maximal isometric knee extension or a 3-min all-out cycling test. Physiological variables were unchanged between conditions and although RPE tended to be greater and intrinsic motivation reduced when mentally fatigued, this did not impact upon maximal anaerobic performance. The findings of the present study suggest that peripheral mechanisms primarily regulate this type of performance. Although previous research indicates that mental fatigue negatively influences submaximal endurance exercise, it seems that it does not impair maximal anaerobic exercise tasks.

Chapter Four: Superior Inhibitory Control and Resistance to Mental Fatigue in Professional Road Cyclists

Declaration for Thesis Chapter Four

In the case of Chapter Four, Kristy Martin contributed to the study design, data collection, statistical analysis and preparation of the manuscript, the extent of this contribution was 60%.

The following co-authors also contributed to the work; Walter Staiano (study design, data collection, statistical analysis, preparation of manuscript), Australian Institute of Sport – Paolo Menaspa, David Martin, Shona Halson (provision of athletes, data collection), Samuele Marcora (study design, preparation of manuscript), Ben Rattray (study design, data collection, preparation of manuscript), Kevin Thompson (preparation of manuscript), Richard Keegan (preparation of manuscript) and Tom Hennessey (data collection). Tom Hennessey is a research student at the University of Canberra.

Candidate's signature ____________________________ **Date** ____________________

Declaration by co-authors

The undersigned hereby certify that:

1. The above declaration correctly reflects the nature and extent of the candidate's contribution to this work, and the nature of the contribution of each of the co-authors
2. They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise
3. They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication
4. There are no other authors of the publication per these criteria
5. Potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit
6. The original data is stored at the University of Canberra Research Institute for Sport and Exercise and will be held for at least five years

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4.1 Foreword

The previous chapter discussed the types of exercise performance that are impaired and unimpaired by mental fatigue. It was concluded that prolonged and submaximal endurance exercise is most affected by mental fatigue, whereas short duration and maximal intensity exercise is not. A limitation of the previous chapter, and previous mental fatigue and physical performance research in general, is the exclusive use of recreational and moderately trained participants. This chapter attempts to address this limitation, and determine whether the calibre of the athlete or participant moderates the negative effects of mental fatigue on rating of perceived exertion and endurance performance. Eleven professional cyclists and nine recreational cyclists completed a 30 min incongruent Stroop task, designed to induce mental fatigue. Performance on the Stoop task, and a subsequent cycling time trial was compared between the levels of athlete, as well as between mental fatigue and control conditions. This study has been accepted for publication and was first published online in July 2016.

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4.2 Abstract

Purpose: Given the important role of the brain in regulating endurance performance, this comparative study sought to determine whether professional road cyclists have superior inhibitory control and resistance to mental fatigue compared to recreational road cyclists.

Methods: After preliminary testing and familiarization, 11 professional and 9 recreational road cyclists visited the lab on two occasions to complete a modified incongruent Stroop task (a cognitive task requiring inhibitory control) for 30 min (mental exertion condition), or an easy cognitive task for 10 min (control condition) in a randomized, counterbalanced cross-over order. After each cognitive task, participants completed a 20-min time trial on a cycle ergometer. During the time trial, heart rate, blood lactate concentration, and rating of perceived exertion (RPE) were recorded.

Results: The professional cyclists completed more correct responses during the Stroop task than the recreational cyclists (705±68 vs 576±74, p=0.001). During the time trial, the recreational cyclists produced a lower mean power output in the mental exertion condition compared to the control condition (216±33 vs 226±25 W, p=0.014). There was no difference between conditions for the professional cyclists (323±42 vs 326±35 W, p=0.502). Heart rate, blood lactate concentration, and RPE were not different between the mental exertion and control conditions in both groups.

Conclusion: The professional cyclists exhibited superior performance during the Stroop task which is indicative of stronger inhibitory control than the recreational cyclists. The professional cyclists also displayed a greater resistance to the negative effects of mental fatigue as demonstrated by no significant differences in perception of effort and time trial performance between the mental exertion and control conditions. These findings suggest that inhibitory control and resistance to mental fatigue may contribute to successful road cycling performance. These psychobiological characteristics may be either genetic and/or developed through the training and lifestyle of professional road cyclists.

Superior Inhibitory Control and Resistance to Mental Fatigue in Professional Road Cyclists

4.3 Introduction

Comparisons of professional and recreational or elite and sub-elite athletes have been used to determine the factors that may contribute to successful sporting performance. With specific reference to endurance performance, several comparative studies have shown that elite athletes differ from recreational ones in a number of physiological characteristics including maximal oxygen consumption (VO_{2max}), stroke volume, muscle capillary density and aerobic enzyme activity, lactate threshold and gross mechanical efficiency (Joyner and Coyle 2008).

A limitation of this body of research is the almost exclusive examination of factors ‘below the neck’. To the best of our knowledge, the only comparative study of the brain in endurance athletes has shown increased grey matter volume in the medial temporal lobe compared to both non-exercising individuals and martial artists (Basner and Dinges 2011). With regards to cognitive function, it has been recently demonstrated that faster runners during an ultramarathon outperform slower runners in terms of motor inhibition and suppression of irrelevant information, with no group differences in selective attention and working memory (Cona, Cavazzana et al. 2015). These findings suggest that successful endurance performance may require superior inhibitory control, a cognitive process essential for self-regulation of behaviour (Muraven and Baumeister 2000). This proposal is plausible if we consider endurance competitions as self-regulated tasks that require the inhibition of aversive feelings (like dyspnea, muscle pain, and thermal discomfort), the urge to quit and other negative thoughts in order to reach the goal of winning or performing at the best of one’s own ability (Marcora 2009).

The problem with endurance competitions and other self-regulated tasks requiring inhibitory control and other effortful cognitive processes is that, over time, they can induce a state of mental fatigue or “ego depletion” (Muraven and Baumeister 2000). Mental fatigue has been usually constructed as the negative effects of prolonged mental exertion on mood (e.g., feelings of tiredness and lack of energy) and/or performance during cognitive tasks requiring vigilance and other effortful cognitive processes (Boksem and Tops 2008). However, we and others have recently demonstrated that mental fatigue is also associated with a higher perception of effort and reduced performance during physical endurance tasks (Marcora, Staiano et al. 2009, MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014, Smith, Marcora et al. 2014). For example, we demonstrated that performing for 30 min a cognitive task requiring strong response inhibition increases perception of effort (RPE) and reduces performance in a subsequent 5K time trial on a treadmill compared to a 30-min cognitive task in which no response inhibition is required (Pageaux, Lepers et al. 2014). Therefore, superior resistance to mental fatigue should provide an advantage to endurance athletes. However, to date, most research on the characteristics of successful endurance athletes have focused on the physiological factors associated with superior resistance to muscle fatigue, e.g. a high percent of type I muscle fibres (Joyner and Coyle 2008). We are not aware of any experimental study investigating the effects of prolonged mental exertion on RPE and endurance performance in professional endurance athletes. This is unfortunate because a comparison between professional and recreational endurance athletes is necessary to test the hypothesis that superior resistance to mental fatigue is a psychobiological characteristic of successful endurance athletes.

The first aim of the present study was to further investigate the association between inhibitory control and endurance performance by comparing the performance of professional and recreational road cyclists in a 30-min modified incongruent colour-word Stroop task, a cognitive task requiring strong response inhibition. Based on previous findings of an association between performance level and inhibitory control in ultramarathon runners (Cona, Cavazzana et al. 2015), we hypothesised that professional cyclists perform better in the Stroop task than their recreational counterparts. The second aim of this study was to determine whether superior resistance to mental fatigue is a psychobiological characteristic of successful endurance athletes. Because resistance to mental fatigue should provide an advantage to endurance athletes, we hypothesised that, compared to the recreational cyclists, the professionals are more resistant to the negative effects of prolonged mental exertion on RPE and performance during a subsequent 20-min time trial on a cycle ergometer.

4.4 Methods

Participants

Eleven professional, male road cyclists (23.4±6.4 years, 68.2±4.3 kg, 180±7 cm, peak power output 414±48 W, > 5 training sessions per week, > 500 km per week, > 5 years of cycling experience) and nine recreational male road cyclists (25.6±5.3 years, 80.7±11.3 kg, 177±7 cm, peak power output 261±28 W, ~3 training sessions per week, ~ 80 km per week, an average of 2 years of cycling experience) volunteered to participate in this study. Taking into account each participant peak power output and training history, and in line with guidelines designed to help describe the performance level of participants in sports science research (De Pauw, Roelands et al. 2015), the professional cyclists were classified as performance level 5 and the recreational cyclists were classified between performance level 1 and 2. Each participant gave written informed consent prior to commencing testing. The study design and procedures were approved by the University of Canberra Committee for Ethics in Human Research. All participants received written instructions describing the study procedures but were naive to its true aims and hypotheses. Participants were led to believe the main aim of the study was to investigate the effects of mental exertion on physiological responses during the time trial. No further specifics were provided. At the end of the final visit, participants were debriefed and asked not to discuss the real aims of the study with other participants. One of the professional cyclists was unable to complete all visits due to injury. This participant's data have been included only in the analysis of Stroop performance.

Experimental Protocol

A randomised crossover design was used for the experimental component of the present study. The order of the experimental treatment (mental exertion/control or control/mental exertion) was randomly allocated based on balanced permutations generated by a web-based computer program (www.randomization.com). Participants were required to visit the laboratory on four occasions (Fig 1), in a period no longer than two weeks between the first and last visit. Testing during visits 3 and 4 was completed at the same time of the day. During the initial visit, participants completed an incremental exercise test, and became familiar with the Stroop task and all psychological, perceptual and physiological measures. During the second visit, participants were familiarised with the time trial. During visits 3 and 4, participants completed the baseline mood questionnaire, followed by either the Stroop task or the control task. After rating their motivation related to the upcoming time trial, participants were moved to a cycle ergometer where they completed a standardized warm-up and a 20 min time trial. After cooling down, participants rated again their current mood. Prior to visits three and four, participants were instructed to drink 35 ml of water per kilogram of body weight, sleep for at least 7 h, refrain from the consumption of alcohol, and avoid any vigorous exercise the day before visiting the laboratory. Participants were also instructed to avoid any caffeine and mentally demanding tasks for at least 3 h before testing. The day of visit 3, participants were asked to record the time and content of the meals consumed before testing, and to keep them consistent the day of visit 4. At the beginning of visits 3 and 4, participants were asked to complete a checklist to ascertain that they had complied with the instructions given to them. Participants were also asked to declare if they had taken any medication/drug or had an acute illness, injury, or infection on the day.

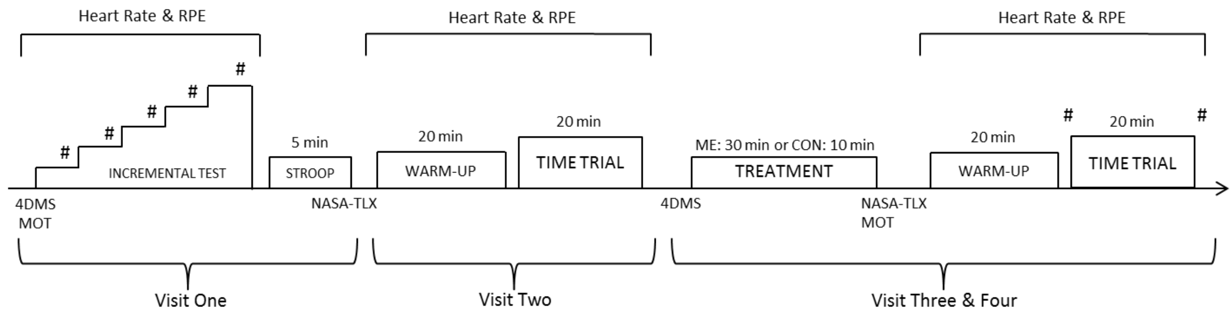

Figure 4.1 Schematic of the experimental protocol. # - Blood lactate sample. 4DMS - The four dimensional mood scale. MOT – Rating of motivation related to the time trial. NASA-TLX - The National Aeronautics and Space Administration Task Load Index. RPE – Rating of perceived exertion.

Experimental Treatment

The mental exertion condition consisted of 30 min of modified incongruent version of the Stroop colour-word task. Participants performed this cognitive task at a computer, whilst sitting comfortably in a quiet, dimly lit room. This Stroop task consists of four words (yellow, blue, green, red) serially presented on the computer screen, displayed until the participant responded, followed by a 1.5 s rest interval. Participants were instructed to press one of four coloured buttons on the keyboard (yellow, blue, green, red), with the correct response being the button corresponding to the ink colour (either yellow, blue, green, red) of the word presented on the screen. For example, if the word blue appeared in yellow ink, the yellow button had to be pressed. If, however, the ink colour was red, the button to be pressed was the button linked to the written word, not the ink colour (e.g. if the word blue appears in red, the button blue was to be pressed). If the ink colour was blue, green or yellow, then the correct button pressed matched the ink colour. The word presented and its ink colour was randomly selected by the computer. Twenty practice attempts were allowed to ensure the participant fully understood the instructions. The Stroop task was also performed for 5 min during familiarization in visit 1. Participants were instructed to respond as quickly and accurately as possible. Visual feedback was given after each word in the form of correct or incorrect response, reaction time, and accuracy so far. Responses faster than 200 ms were excluded from the analysis as it is likely the participant responded before seeing the word (Whelan 2010). Responses over 2 s were recorded as lapses and removed from the analysis. This value was chosen arbitrarily as the best trade value to normalise the data while maintaining the greatest number of responses and highest statistical power (Basner and Dinges 2011). Average reaction time for the correct responses and accuracy (percentage of correct responses) were calculated for each of six 5-min epochs during the 30 min Stroop task (5^{th}, 10th, 15th, 20th, 25th and 30^{th} min). The total number of correct responses were also calculated for the entire 30 min Stroop task.

The control condition consisted of an easy cognitive task performed under the same conditions as the Stroop task. Participants were instructed to sit quietly in front of the computer screen and focus for 10 min on the centred black cross, displayed on a white background.

Incremental Exercise Test and Time Trial

During the initial visit, participants underwent an incremental exercise test to assess peak power output. The incremental exercise test was completed on a cycle ergometer (Lode Excalibur Sport, Lode, The Netherlands) with the test beginning at 125 W and increasing by 25 W every 3 min until volitional exhaustion.

Participants completed the time trial during each of the other three visits to the laboratory. A standardised warm-up was completed by all participants prior to each time trial using an SRM electromagnetically braked ergometer (High-Performance Ergometer, Schoberer Rad MeBtechnik, Germany). The time trial was then completed on another electromagnetically braked cycle ergometer (Velotron Pro, RacerMate Inc., USA). All the ergometers were fitted to replicate the participants' bike positions. Participants were instructed to cover as much distance as possible over 20 min. The time trial began in a standard gear; however, participants were free to alter gearing throughout the time trial. A timer was placed to the front left of participants and remained visible during the time trial. Participants were blinded to all other performance and physiological data. A fan was placed behind the timer and turned on at participant's request, and water was provided ad libitum.

During visits 3 and 4, a researcher who was blind to the experimental treatment received by the participants provided verbal encouragement throughout the test. This researcher was consistent within participants. Another researcher recorded power output at the 1st, 4th, 8th, 12th, 16th and 20th min of the time trial. Average speed and total distance covered during the time trial were also recorded.

Physiological and Perceptual Measures

Capillary blood samples were collected before and straight after completion of time trial during visits 3 and 4. Samples were analysed immediately for blood lactate concentration using the Lactate Pro 2 (Arkray, Japan) analyser. During visits 3 and 4, heart rate was recorded at the end of the warm-up, and during the final 15 s of the 1st, 4th, 8th, 12th, 16th and 20th min of the time trial using a heart rate monitor fitted with a chest strap (T34 non-coded heart-rate transmitter, Polar, Finland).

Rating of perceived exertion was measured using the Borg 6-20 scale (Borg 1970). During visit 1, RPE was anchored during the incremental exercise test using standard procedures (Noble and Robertson 1996). During visits 3 and 4, RPE was measured at the end of the warm-up, and during the final 15 s of the 1st, 4th, 8th, 12th, 16th and 20th min of the time trial. At the appropriate time point, participants were asked to point on a large Borg 6-20 scale the number corresponding to their perception of effort defined as "the conscious sensation of how hard, heavy, and strenuous exercise is" (Marcora 2010).

Psychological Measures

The National Aeronautics and Space Administration Task Load Index (NASA-TLX) was used to assess subjective workload of the cognitive tasks (Hoonakker, Carayon et al. 2011). The NASA-TLX is composed of six subscales: mental demand (How much mental and perceptual activity was required?), physical demand (How much physical activity was required?), temporal demand (How much time pressure did you feel due to the rate or pace at which the task occurred?), performance (How successful do you think you were in accomplishing the goals of the task set by the experimenter?), effort (How hard did you have to work to accomplish your level of performance?)

and frustration (How irritating or annoying did you perceive the task?). Participants were asked to score each of the items on a scale divided into 20 equal intervals anchored by the bipolar descriptors high and low. This score was multiplied by 5, resulting in a final score between 0 and 100 for each of the subscales. Only the mental demand, temporal demand, effort and frustration subscales were used in the present study.

The Four Dimensional Mood Scale (4DMS) was used to assess changes in mood from the beginning to the end of visits 3 and 4. The 4DMS consists of 20 adjectives and is designed to measure positive energy, tiredness, negative arousal, and relaxation. Participants rated each adjective on the extent to which it described their current mood state using a 5-point Likert scale. Reliability and validity of this scale have been previously reported (Huelsman, Nemanick et al. 1998).

Motivation related to the time trial was measured using a single item ("I am motivated to do the time trial") scored on a 5-point Likert scale (0 = not at all, 1 = a little bit, 2 = somewhat, 3 = very much, 4 = extremely).

Statistical Analysis

All data are presented as mean ± one standard deviation unless otherwise stated. Assumptions of statistical tests such as normal distribution and sphericity of data were checked as appropriate. Greenhouse-Geisser correction to the degrees of freedom was applied when violations to sphericity were present. Independent samples t-tests were used to determine the effect of group (professional and recreational cyclists) on the total number of correct responses during the Stroop task. A mixed 2 x 6 ANOVA was used to determine the effects of group and time (5th, 10th, 15th, 20th, 25th and 30th min) for reaction time during the Stroop task. Mixed 2 x 2 ANOVAs were used to determine the effects of group and condition (mental exertion vs. control) on the NASA TLX subscales, motivation related to the time trial, and average speed and total distance covered during the time trial. A mixed 2 x 2 x 2 ANOVA was used to determine the effects of group, condition and time (before and after the time trial) for blood lactate concentration. A mixed 2 x 2 x 2 ANOVA was used to determine the effects of group, condition and time (beginning and end of the visit) for mood. Mixed 2 x 2 x 6

ANOVAs were used to determine the effects of group, condition and time (1st, 4th, 8th, 12th, 16th and 20th min) on heart rate, RPE and power output during the time trial. Significant interactions were followed up with Bonferroni tests as appropriate. If significant interactions were not found, most relevant main effects are reported. Significance was set at 0.05 (2-tailed) for all analyses. The effect sizes for the repeated measures ANOVAs were calculated as partial eta squared (η^2p), using the small=0.02, medium=0.13 and large=0.26 interpretation for effect size (Bakeman 2005). All data analysis was conducted using the statistical packages for social science (SPSS version 20).

4.5 Results

Psychological Responses

Using the NASA-TLX, the Stroop task was rated as being more mentally demanding (grand mean mental exertion 77±11 and control 24±23, main effect of condition, $p<0.001$, $\eta^2p=0.838$), more temporally demanding (grand mean mental exertion 63±16 and control 12±8, main effect of condition, $p<0.001$, $\eta^2p=0.887$) and more frustrating (grand mean mental exertion 56±23 and control 19±19, main effect of condition, $p<0.001$, $\eta^2p=0.749$) than the control task, with no significant main effects of group or group x condition interactions. There was, however, a significant group x condition interaction for effort ($p=0.033$, $\eta^2p=0.240$). Follow-up tests revealed that both the professional (76±19, $p<0.001$, $\eta^2p=0.904$) and the recreational cyclists (65±20, $p=0.001$, $\eta^2p=0.745$) rated the Stroop task as more effortful than the control task, although the recreational cyclists (24±20) rated the control task as more effortful than the professional cyclists (10±19) did ($p=0.046$, $\eta^2p=0.213$).

Analysis of the 4DMS revealed a decrease over time in positive energy (grand mean pre 3.0±0.7 and post 2.4±0.8, main effect of time, $p<0.001$, $\eta^2p=0.361$) and relaxation (grand mean pre 3.3±0.7 and post 3.0±0.8, main effect of time, $p=0.014$, $\eta^2p=0.165$) with no significant main effects of group and condition, and no significant interactions. Tiredness increased over time (grand mean pre 2.2±0.5 and post 3.6±0.5, main effect of time, $p<0.001$, $\eta^2p=0.771$), with no significant main effects of group and condition, and no significant interactions. There were no significant main effects of time, group and condition, and no significant interactions for negative arousal (overall grand mean: 1.5±3.4). There were no significant main effects of group and condition, and no group x condition interaction on motivation related to the time trial (overall grand mean: 2.3±0.8).

Stroop Performance

There was a significant group x time interaction for reaction time ($p=0.023$, $\eta^2p=0.165$) (Fig 2a). Follow–up tests revealed that reaction time decreased over time in both the professional ($p<0.001$, $\eta^2p=0.671$) and recreational cyclists ($p=0.019$, $\eta^2p=0.278$). However, the professional cyclists showed a greater decrease in reaction time over time compared to the recreational cyclists. There were no significant main effects of group and time, and no significant group x time interaction for accuracy (Fig 2b). In total, professional cyclists completed more correct responses than recreational cyclists ($p=0.001$, $\eta^2p=0.481$) during the Stroop task (Fig 3).

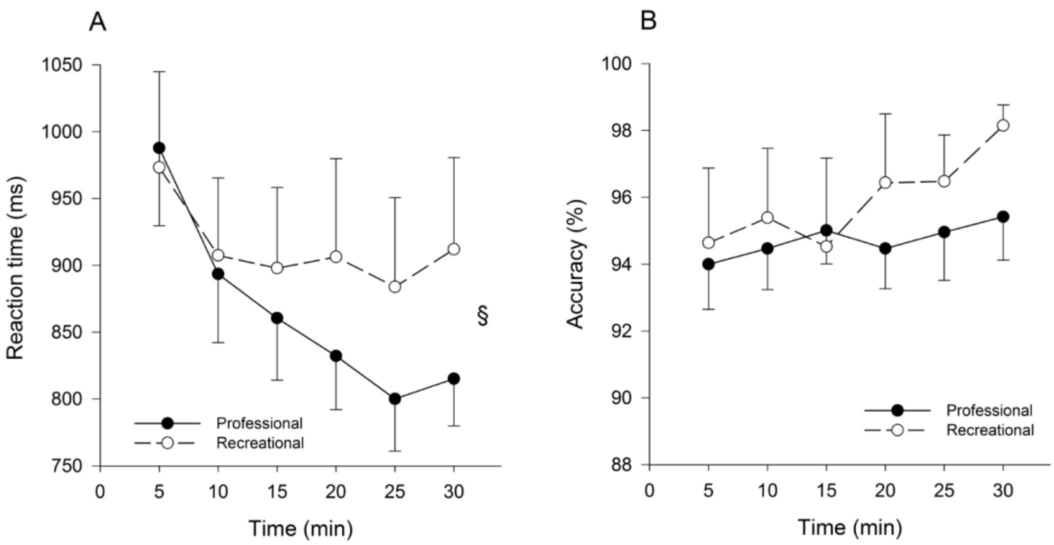

Figure 4.2 Reaction time (A) and accuracy (B) over time during the 30-min Stroop task in professional (n= 11) and recreational (n=9) road cyclists. § Significant group x time interaction ($p < 0.05$). Data are presented as mean ± SEM.

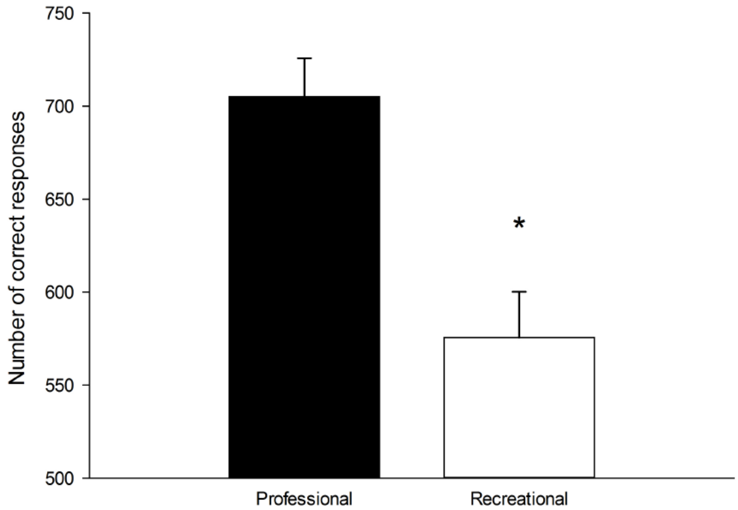

Figure 4.3 Total number of correct responses during the 30-min Stroop task in professional (n=11) and recreational (n=9) road cyclists. * Significant difference between groups ($p < 0.05$). Data are presented as mean ± SEM.

Time Trial Performance

There was a significant group x condition interaction for average speed during the time trial ($p=0.017$, $\eta^2p=0.293$). Follow-up tests revealed that the professional cyclists were faster than their recreational counterparts in both the mental exertion ($p<0.001$, $\eta^2p=0.822$) and control condition ($p<0.001$, $\eta^2p=0.857$). In the professional cyclists, average speed during the time trial was not significantly different between conditions (mental exertion: 44.1±2.2 km.hr-1, control: 44.3±1.8 km.hr-1, $p=0.261$, $\eta^2p=0.138$). On the contrary, the recreational cyclists were significantly slower in the mental exertion condition (34.3±2.6 km.hr-1) than in the control condition (35.5±1.9 km.hr-1, $p=0.003$, $\eta^2p=0.683$).

Similarly, there was a significant group x condition interaction for total distance covered during the time trial ($p=0.019$, $\eta^2p=0.285$). Follow-up tests revealed that the professional cyclists covered more distance than the recreational cyclists in both the mental exertion ($p<0.001$, $\eta^2p=0.821$) and control condition ($p<0.001$, $\eta^2p=0.867$). In the professional cyclists, total distance covered during the time trial was no significantly different between conditions (mental exertion: 14.8±0.7 km, control: 14.8±0.6 km, $p=0.223$, $\eta^2p=0.160$). On the contrary, the recreational cyclists covered significantly less distance in the mental exertion condition (11.4±0.9) than in the control condition (11.8±0.6 km, $p=0.006$, $\eta^2p=0.633$).

There was a group x condition x time interaction for power output during the time trial ($p=0.049$, $\eta^2p=0.153$) (Fig 4). Follow-up tests revealed that there were no significant main effects of condition ($p=0.675$, $\eta^2p=0.020$) and time ($p=0.484$, $\eta^2p=0.072$) in the professional cyclists. In the recreational cyclists, power output during the time trial was significantly lower in the mental exertion condition than in the control condition (main effect of condition, $p=0.017$, $\eta^2p=0.530$) and increased significantly over time in both conditions (main effect of time, $p=0.003$, $\eta^2p=0.486$).

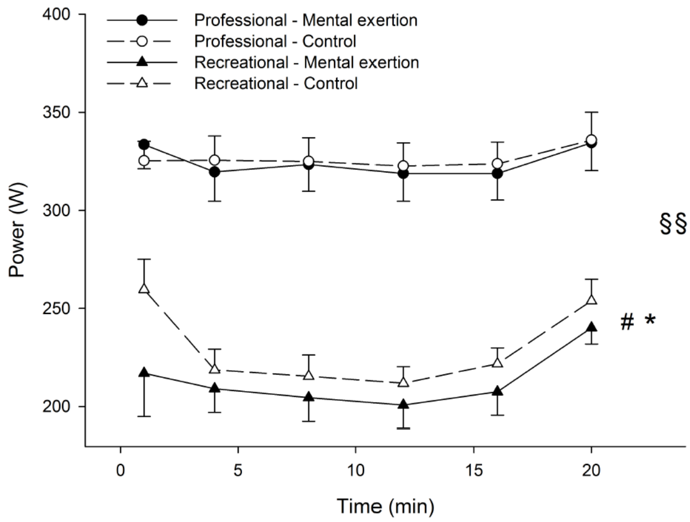

Figure 4.4 Effect of prior mental exertion on power output during the 20-min time trial in professional (n= 10) and recreational (n=9) road cyclists. $$ Significant group x condition x time interaction ($p < 0.05$). # Significant main effect of time in recreational cyclists ($p < 0.05$). * Significant main effect of condition in recreational cyclists ($p < 0.05$). Data are presented as mean ± SEM.

Physiological and Perceptual Responses

There were no significant interactions, and no significant main effects of group and condition for blood lactate concentration which increased significantly from before (grand mean: 3.2±1.2 mmol.l-1) to after (grand mean: 9.5±2.5 mmol.l-1) the time trial (main effect of time $p<0.001$, $\eta^2p=0.846$).

There were no significant group x condition x time and group x condition interactions for heart rate during the time trial (Fig 5). There was, however, a significant group x time interaction ($p=0.010$, $\eta^2p=0.234$). Follow-up tests revealed that heart rate increased over time in both the professional ($p<0.001$, $\eta^2p=0.773$) and the recreational cyclists ($p<0.001$, $\eta^2p=0.0.818$). The professional cyclists had higher heart rates than the recreational cyclists at minutes 4 ($p=0.002$, $\eta^2p=0.245$), 8 ($p=0.001$, $\eta^2p=0.275$), 12 ($p<0.001$, $\eta^2p=0.371$) and 16 ($p<0.001$, $\eta^2p=0.316$) of the time trial.

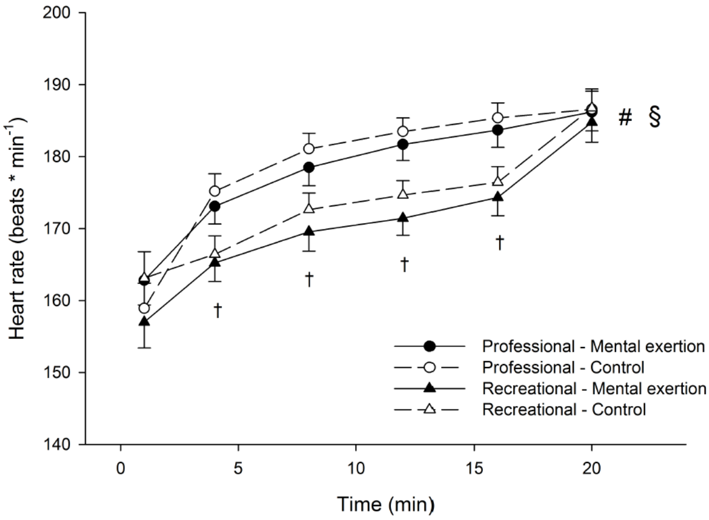

Figure 4.5 Effect of prior mental exertion on heart rate during the 20-min time trial in professional (n=10) and recreational (n=9) road cyclists. $ Significant group x time interaction ($p < 0.05$). # Significant main effects of time in professional and recreational cyclists ($p < 0.05$). † Significant simple main effects of group ($p < 0.05$). Data are presented as mean ± SEM.

There were no significant group x condition x time and group x condition interactions for RPE during the time trial (Fig 6). A significant group x time interaction was found on RPE during the time trial ($p=0.005$, $\eta^2p=0.272$). Follow-up tests reveal that RPE increased over time for both the professional ($p<0.001$, $\eta^2p=0.748$) and recreational cyclists ($p<0.001$, $\eta^2p=0.895$). The professional cyclists reported significantly higher RPE than recreational cyclists at minutes 1 ($p<0.001$, $\eta^2p=0.338$), 4 ($p<0.001$, $\eta^2p=0.444$), 8 ($p<0.001$, $\eta^2p=0.321$), 12 ($p=0.001$, $\eta^2p=0.269$) and 16 ($p=0.016$, $\eta^2p=0.160$) of the time trial.

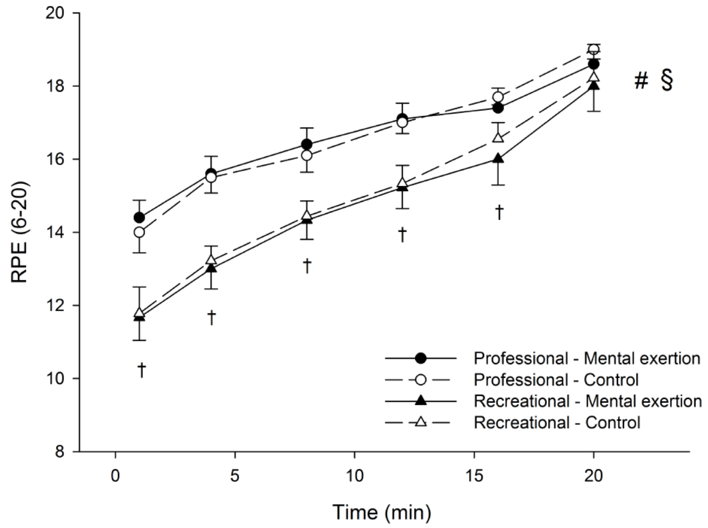

Figure 4.6 Effect of prior mental exertion on rating of perceived exertion (RPE) during the 20-min time trial in professional (n =10) and recreational (n =9) road cyclists. $ Significant group x time interaction ($p < 0.05$). # Significant main effects of time in professional and recreational cyclists ($p < 0.05$). †Simple main effects of group ($p < 0.05$). Data are presented as mean ± SEM.

4.6 Discussion

As we hypothesised, the professional road cyclists performed better in the Stroop task than their recreational counterparts. We also found that, compared to the recreational cyclists, the professionals were more resistant to the negative effects of prolonged mental exertion on perception of effort and performance during a subsequent 20-min time trial on a cycle ergometer. These findings suggest that successful endurance performance may require superior inhibitory control and resistance to mental fatigue.

Inhibitory Control

Analysis of reaction time showed that professional cyclists progressively improved performance throughout the 30-min Stroop task whilst recreational cyclists improved their performance only over the first 10 minutes. Because accuracy was similar between the two groups, overall the professional cyclists completed significantly more correct responses than the recreational cyclists during the Stroop task. The fact that professional and recreational cyclists reported similar levels effort in relation to the Stroop task suggests that superior performance was not due to different levels of task engagement. Therefore, we propose that superior Stroop performance is indicative of better inhibitory control in professional cyclists compared to recreational ones. Our findings concur with the results of a recently published study in which the median-split technique was used to divide 30 participants into faster and slower runners based on their ranking in an ultramarathon (Cona, Cavazzana et al. 2015). Analysis of a battery of cognitive tests administered before their participation in the ultramarathon revealed that faster runners performed better than the slower runners in trials requiring inhibition of inappropriate motor responses, and were more effective in suppressing irrelevant information during dual-task performance. The cognitive performance of faster runners also seems to be less affected by emotional stimuli. Overall, our results and the recent findings of (Cona, Cavazzana et al. 2015) suggest that superior inhibitory control is a psychobiological characteristic of successful endurance athletes. At an anecdotal level, this association is plausible because an endurance athlete with better inhibitory control is more likely to persist with strenuous training programs, dietary restrictions, and limitations to his/her social life while also being better able to exert control over his/her thoughts, feelings and actions during competitions.

As in other comparative studies, we can only speculate on why successful endurance athletes have superior inhibitory control. Previous studies of self-regulation suggest that inhibitory control may be a largely genetic and stable trait. Children who demonstrated greater inhibitory control by forgoing an immediate reward, for double the reward a period of time later (Mischel, Ebbesen et al. 1972) tended to have better exam scores (Mischel, Shoda et al. 1989), higher levels of education (Ayduk, Mendoza-Denton et al. 2000) and healthier body mass index (Schlam, Wilson et al. 2013) later in life than those children who chose the immediate single reward. A study of monozygotic and dizygotic twins indicated that individual differences in effortful cognitive processes including inhibitory control are almost entirely genetic in origin and largely unaffected by general intelligence or perceptual speed (Friedman, Miyake et al. 2008). Genetic variation has also been associated with individual differences in brain activity related to response inhibition in Go/No-Go tasks (Anokhin, Heath et al.

2004). It is, therefore, plausible that genetic factors, selected through talent identification programs and/or success in competitions, could explain the superior inhibitory control we observed in professional road cyclists.

Although inhibitory control seems to have high heritability, other research suggests that aerobic training and the lifestyle of professional athletes may also contribute. With regards to aerobic training, a structural neuroimaging study in elderly people demonstrated that 6-month aerobic training increases the volume of the anterior cingulate cortex (ACC) (Colcombe, Erickson et al. 2006), a cortical area associated with Stroop performance (Gruber, Rogowska et al. 2002, Laird, McMillan et al. 2005). Furthermore, neural efficiency may also improve with aerobic training as a functional neuroimaging study showed reduced activation of the ACC during an effortful cognitive tasks in fit older adults compared to unfit individuals (Wong, Chaddock-Heyman et al. 2015). These cortical adaptations may mediate the specific effects of aerobic training on cognitive tasks that require inhibitory control and other effortful cognitive processes (Kramer, Hahn et al. 1999). Although more neuroimaging research in young adults is required, these studies provide some support to our speculation that the high aerobic training load required by professional road cycling may be in part responsible for the superior Stroop performance we observed in the present study.

With regards to lifestyle, it is likely that professional road cyclists would encounter situations requiring self-regulation and inhibitory control on a more consistent basis than recreational ones. Professional endurance athletes must monitor their diet, alcohol intake, refrain from smoking, ensure they get enough rest and follow a strict physical training program. This consistent self-regulation of behaviour may strengthen inhibitory control across the physical and cognitive domains as demonstrated by research on self-regulatory training. For example, college students who spent 2 weeks doing one of three self-regulatory exercises (monitoring and improving posture, regulating mood, or monitoring and recording eating) performed better than a control group in a physical endurance task following a thought-suppression task (Muraven, Baumeister et al. 1999).

Resistance to Mental Fatigue

The second aim of this study was to test the hypothesis that professional endurance athletes have superior resistance to mental fatigue compared to their recreational counterparts. We tested this hypothesis by asking our participants to perform the Stroop task for 30 minutes and measuring the effects of this prolonged mental exertion on perception of effort and performance during a subsequent 20-min time trial on a cycle ergometer. Consistent with previous research on mental fatigue and self-paced endurance performance (MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014), the recreational cyclists produced a lower power output for the same RPE during the time trial following the Stroop task compared to the control task. The professional cyclists, however, did not record any difference in either RPE or time trial performance between the mental exertion and control conditions. These results suggest that the professional cyclists were not mentally fatigued after performing the Stroop task for 30 minutes. We can exclude lower engagement during the Stroop task as a possible explanation for the lack of mental fatigue in the professionals. Firstly, their ratings of effort and mental demand in relation to the Stroop task were not significantly different from those of the recreational cyclists. Secondly, as discussed earlier, Stroop performance was actually better in professional road cyclists compared to their recreational counterparts. Therefore, superior resistance to mental fatigue, not lower exertion, is the most likely explanation for no negative effects of the Stroop task on perception of effort and endurance performance in professional road cyclists. Superior resistance to mental fatigue may also explain why the professionals responded more quickly than recreational cyclists in the latter stages of the Stroop task.

We are not aware of studies on the heritability of resistance to mental fatigue. However, several studies have demonstrated that the negative effects of sleep deprivation on brain activity and cognitive performance show large and stable individual differences, possibly related to adenosinergic mechanisms (Rétey, Adam et al. 2006). Given that adenosinergic mechanisms are also involved in mental fatigue (Lorist and Tops 2003), future research should establish whether genetic factors could explain the superior resistance to mental fatigue we observed in professional road cyclists.

With regards to environmental factors, our previous discussion on the effects of aerobic training on ACC morphology and function is relevant to superior resistance to mental fatigue in professional road cyclists. This cortical area has been associated with both mental fatigue (Lorist, Boksem et al. 2005, Lim, Wu et al. 2010) and perception of effort during physical tasks (Williamson, McColl et al. 2001). Therefore, the ACC provides a plausible neurobiological link between prolonged mental exertion, high perception of effort, and reduced endurance performance (Marcora, Staiano et al. 2009). Unfortunately, little is known about the effects of aerobic training on the brain of young adults. It is possible, however, that the high volume and intensity of aerobic training required by professional road cycling may induce morphological and functional adaptations in the ACC that increase resistance to mental fatigue. Further research using neuroimaging methods should test this interesting hypothesis. In addition to high training load, other psychobiological stressors (e.g., competitions, media intrusion, self-regulation of diet and other behaviours) may induce a degree of mental fatigue in a natural setting. Therefore, professional road cyclists may have been more prepared than their recreational counterparts to resist the negative effects of prolonged mental exertion on perception of effort and endurance performance.

Although our findings suggest that superior resistance to mental fatigue may be an important psychobiological characteristic of successful endurance athletes, this does not mean that successful endurance athletes are immune to mental fatigue. A limitation of the current study is that the Stroop task was quite short in duration (30 min) compared to the duration of cognitive tasks traditionally used in mental fatigue research (90 up to 180 min) (Boksem, Meijman et al. 2005, Marcora, Staiano et al. 2009). Furthermore, the improvement in reaction time during the Stroop task suggests that the task became progressively easier (habituation effect). Therefore, mental exertion was far from extreme in the present study. Research on overtraining syndrome clearly suggests that higher levels of psychobiological stress can induce symptoms of mental fatigue (mood disturbances, a higher-than-normal perception of effort during training, and reduced performance) even in elite athletes (Purvis, Gonsalves et al. 2010).

4.7 Practical Applications

The results of the present study may provide a number of novel practical applications. Firstly, given the strong genetic component of inhibitory control, it is possible that the Stroop task and other cognitive tests will be used in conjunction with physiological and anthropometric tests to identify athletes that may be more likely to succeed in endurance sports. The addition of a cognitive aspect to athlete testing would extend the current talent identification process and potentially lead to a more targeted use of athlete funding. Secondly, novel interventions specifically designed to improve inhibitory control and resistance to mental fatigue may help endurance athletes looking to further enhance their performance or those struggling with self-regulation of their behaviour. Such interventions may include the teaching of self-regulatory skills as well as novel training methods in which mental exertion is combined with aerobic training (Marcora, Staiano et al. 2015).

Chapter Five: Self-Regulatory Behaviours Predict Inhibitory Control and Maintenance of Endurance Performance with Mental Fatigue

Declaration for Thesis Chapter Five

In the case of Chapter Five, Kristy Martin contributed to the study design, data collection, statistical analysis and preparation of the manuscript, the extent of this contribution was 85%.

The following co-authors also contributed to the work; Ben Rattray (study design, preparation of manuscript), Richard Keegan (preparation of manuscript) and Kevin Thompson (preparation of manuscript). None of the co-authors are students.

Candidate's signature ___________________________ **Date** ___________________

Declaration by co-authors

The undersigned hereby certify that:

1. The above declaration correctly reflects the nature and extent of the candidate's contribution to this work, and the nature of the contribution of each of the co-authors
2. They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise
3. They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication
4. There are no other authors of the publication per these criteria
5. Potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit
6. The original data is stored at the University of Canberra Research Institute for Sport and Exercise and will be held for at least five years

Ben Rattray **Date:** 09·11·2016

Richard Keegan **Date:** 09·11·2016

Kevin Thompson **Date:** 09·11·2016

5.1 Foreword

The previous chapter examined whether the calibre of the athlete or participant moderates the negative effects of mental fatigue on rating of perceived exertion and endurance performance. Chapter Four found that the professional cyclists displayed a greater resistance to mental exertion, demonstrated by the lack of difference in rating of perceived exertion and time trial performance between mental fatigue and control conditions. The professional cyclists also performed better in the Stroop task than the recreational cyclists, suggesting a greater capacity for self-regulation. The following chapter sought to extend the suggestion that self-regulation may be important for both cognitive and physical performance when mentally fatigued. On separate occasions, twenty-four participants completed 90 min of a mentally fatiguing cognitive task, or 90 min of a less demanding control task, followed by a test of cycling time to exhaustion. The degree to which participants undertook behaviours of self-regulation were quantified, and were tested for associations to both cognitive and physical performance when mentally fatigued.

5.2 Abstract

Introduction: Mental fatigue has a detrimental effect on cognitive performance and attention, and more recently, has also been shown to impair endurance performance including both time to exhaustion tasks and self-paced time trials. A recent study however, reported that when compared to recreational endurance athletes, professional endurance athletes performed better on a mentally fatiguing task of inhibitory control and an endurance task following prior mental exertion. The aim of the present study was to determine whether lifestyle behaviours such as cardiorespiratory fitness, training load, occupational cognitive load and emotional load, which require a degree of self-regulation, are associated with (a) inhibitory control and (b) resistance to mental fatigue.

Methods: Twenty-four participants gave informed consent to participate in a randomized, crossover design study. On separate occasions participants completed 90 min of either an incongruent Stroop task or a passive control task (watching a documentary). As a marker of endurance performance, participants then completed a cycling time to exhaustion task at 80% of individual peak power output. A number of self-regulatory lifestyle behaviours were quantified for each participant.

Results: Self-reported physical training load and occupational cognitive load significantly predicted mean reaction time during the mental exertion task of inhibitory control ($p=0.028$, adj. $R2=0.232$). Occupational cognitive load, physical training load and cardiorespiratory fitness significantly predicted change in endurance performance following mental exertion ($p=0.005$, adj. $R2=0.456$).

Conclusion: Higher physical training load and occupational cognitive load were associated with greater inhibitory control and better maintenance of endurance performance when mentally fatigued. Higher cardiorespiratory fitness was associated with poorer endurance performance when mentally fatigued. These findings are promising as they suggest that participation in both cognitive and physical exertion may improve both self-regulation and tolerance to mental fatigue.

Self-Regulatory Behaviours Predict Inhibitory Control and Maintenance of Endurance Performance with Mental Fatigue

5.3 Introduction

Mental fatigue is described as a change in psychobiological state caused by prolonged periods of demanding cognitive activity (Marcora, Staiano et al. 2009). Mental fatigue has a detrimental effect on cognitive performance (van der Linden, Frese et al. 2003, Lorist, Boksem et al. 2005) and attention (Boksem, Meijman et al. 2005), and more recently, has also been shown to impair endurance performance including both time to exhaustion tasks (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, Smith, Marcora et al. 2014) and self-paced time trials (MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014, Martin, Staiano et al. 2016). A recent study however, reported that the time trial performance of professional cyclists was unaffected by prior mental exertion, whilst under the same conditions, poorer time trial performance was recorded in competitive recreational cyclists (Martin, Staiano et al. 2016). Not only did professional cyclists exhibit greater physical tolerance to mental fatigue, they also performed better during a cognitive task of inhibitory control (i.e., the mentally fatiguing task) compared to recreational cyclists. The authors of this study contend that the superior performance on the cognitive task of the professional cyclists might reflect a greater capacity for self-regulation or stronger inhibitory control than the recreational cyclists (Martin, Staiano et al. 2016). In a laboratory setting, inhibitory control is operationalized as the suppression of a dominant or automatic response (Garavan, Ross et al. 1999). More broadly, inhibitory control is the ability to suppress irrelevant or interfering stimuli or impulses (Garavan, Ross et al. 1999), and is a cognitive process essential for self-regulation of behavior (Muraven and Baumeister 2000). Self-regulation is the controlled process that effortfully overrides urges, emotions and automatic response tendencies, and can include planning, coping with stress and persisting at physical and mental tasks (Gailliot 2008).

The superior inhibitory control and resistance to mental fatigue observed in the professional cycling group raises further questions. For instance, do the behaviors of a professional athlete strengthen inhibitory control? And if so, does this adaptation afford athletes greater resistance to mental fatigue? Further, does possessing superior inhibitory control and greater resistance to mental fatigue increase the likelihood of achieving success in an endurance sport? Somewhat similarly, the origin of self-regulatory capacity is often debated. Some studies in this area suggest that self-regulation is a largely stable and genetic trait. For example, children who demonstrated greater inhibitory control by forgoing an immediate reward, for double the reward a period of time later tended to have better exam scores (Mischel, Shoda et al. 1989) and healthier body mass index values later in life (Schlam, Wilson et al. 2013). A study of monozygotic and dizygotic twins indicated that differences in the performance of a cognitive task of inhibitory control appeared almost entirely genetic in origin, and largely unaffected by general intelligence or perceptual speed (Friedman, Miyake et al. 2008). Likewise, others report that genetic factors account for between 40% and 56% of the variance in self-regulation (Beaver, Schutt et al. 2009). In contrast, there is alternative data suggesting that self-regulation may be improved via regular performance of tasks that require self-regulation. For example, a two month exercise program improved performance of a visual tracking task (Oaten and Cheng 2004a) and when participants were required to continuously monitor and maintain good posture for two weeks, handgrip endurance performance also improved compared to a control group (Muraven, Baumeister et al. 1999).

To date, the effect of cardiorespiratory fitness on resistance to mental fatigue has not been examined; however, cardiorespiratory fitness has previously been linked to performance on tasks of inhibitory control (Buck, Hillman et al. 2008, Predovan, Fraser et al. 2012), as well as other aspects of cognitive performance (Colcombe and Kramer 2003). Physical training programs focusing predominantly on aerobic exercise have been associated with improvements in executive function (Smith, Blumenthal et al. 2010), as well as structural (Colcombe, Erickson et al. 2006) and functional changes within the brain (Kramer, Hahn et al. 1999). An individual’s cardiorespiratory response has been suggested to be a better predictor of improvement in cognitive function than training duration (Vidoni, Johnson et al. 2015). In addition, aerobic capacity, but not muscle strength, flexibility or body composition, has been reported to be associated with better mathematic and reading test performance in school children (Castelli, Hillman et al. 2007). On the other hand, studies have shown that improving aerobic capacity does not necessarily lead to improved cognitive performance (Madden, Blumenthal et al. 1989) and a 2006 meta-regression determined no significant relationship between cardiorespiratory fitness and cognitive performance, and suggested that future research focus on other physiological and psychological variables linking physical activity and cognitive performance (Etnier, Nowell et al. 2006).

The aim of the present study was therefore to determine whether certain lifestyle behaviors, which require a degree of self-regulation, are associated with (a) inhibitory control and (b) resistance to mental fatigue. Self-regulated tasks are those which require the inhibition of aversive feelings (i.e. muscle pain, boredom), the urge to quit and other negative thoughts in order to reach the goal of the task (Marcora 2009). This study chose to focus on the self-regulatory behaviors of physical training load, occupational cognitive load and occupational emotional load, as well as the physiological variable cardiorespiratory fitness. Assuming that self-regulation would be responsive to training and experience, we hypothesized that greater self-regulatory lifestyle demands (physical training load, occupational cognitive and emotional load) would be associated with both superior inhibitory control and resistance to mental fatigue. Likewise, those with lower self-regulatory lifestyle demands would exhibit worse inhibitory control and record greater performance decrement with mental fatigue. We further hypothesized that a higher level of cardiorespiratory fitness would be related to greater inhibitory control and resistance to mental fatigue.

5.4 Methods

Participants

Twenty-four participants (9 males and 15 females; age 26 ± 6 yr, height 172 ± 11 cm, body mass 70 ± 12 kg, peak power output 320 ± 63 W for males, 213 ± 39 W for females, maximum oxygen uptake 55 ± 9 ml·kg^{-1}·min^{-1} for males, 44 ± 6 ml·kg^{-1}·min^{-1} for females) gave informed consent to participate in the study. Participants were chosen having all responded to an advertisement placed around the university and local sporting clubs, and having met the inclusion criteria below. Eligibility included being aged between 18 and 40 years; free from any known disease or injury; a non-smoker; and not diabetic or dyslexic. Participants had no history of sleep disorders and were not shift workers. All participants were healthy, but ranged from sedentary to national level athlete. Participants who were currently physically active participated in a variety of sports including cycling, triathlon, rugby, wrestling and powerlifting. Using guidelines which utilize peak power output and maximal oxygen consumption to describe participants within sport science research, the male participants where on average characterized as performance level 3 (De Pauw, Roelands et al. 2015) and the female participants as performance level 2 (Decroix, De Pauw et al. 2016). During each testing session, participants were unaware to the true aims and hypotheses of the study. Participants were informed the study was investigating the effect of prior cognitive activity on cycling time to exhaustion. Participants were informed that the measures of self-regulatory lifestyle behaviors were to be used simply to describe the participant's lifestyle. The study protocol was approved by the University of Canberra Committee for Ethics in Human Research (Project Number 15-26).

Experimental Protocol

For this study we employed a randomized, crossover design and experimental testing took place on three occasions. During the initial testing session participants completed an incremental exercise test to establish maximum oxygen uptake and peak power output. Maximum oxygen uptake was used to describe each participant's cardiorespiratory fitness. Peak power output was used to determine the workload of the endurance task and warm-up, completed in sessions two and three. During session 1, participants completed two questionnaires to determine physical training load and occupational cognitive and emotional load. Participants were introduced to the scales used in subsequent testing sessions and completed a five min familiarization of the modified Stroop task, designed to test inhibitory control and induce mental fatigue. The second and third testing sessions were completed in a randomized order, allocated according to balanced permutations generated by a web-based computer program (http://www.randomization.com). During these sessions participants completed a total of 90 min of either a control or a mental exertion task, completed in 3x30 min blocks. Each 30 min block was separated by two min to allow for manipulation checks to be taken. Ninety minutes of the mental exertion and control task was chosen to match previous research which had successfully induced a state of mental fatigue following a demanding cognitive task of this duration (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, MacMahon, Schücker et al. 2014, Smith, Marcora et al. 2014). Five min after the completion of the 90 min intervention period, participants began the endurance task. A schematic of this protocol is shown in Figure 5.1. Further details regarding the questionnaires used to quantify occupational cognitive and emotional load, the mental exertion and control task, and the endurance task are described below. A single, consistent researcher was present at all testing sessions and provided encouragement at regular intervals during this endurance task. Given the known influence of frequency of encouragement (Andreacci, LeMura et al. 2002) and subliminal priming with actions words (Blanchfield, Hardy et al. 2014) on endurance performance, the same wording of encouragement was used and the timing of delivery was consistent between interventions. During the initial portion of the test the researcher commented "great work, keep going" to the participant. Once the participant reported an RPE of 17 or higher, the frequency of encouragement increased to once every 20 seconds until the termination of the test. In addition to this encouragement, if pedal frequency dropped below 60 rpm, the participant was encouraged to increase pedaling frequency. Although the researcher was not blinded to the intervention completed by the participants on each occasion, the score for each of the self-regulatory lifestyle behaviors was not revealed to the researcher until the time of analysis.

Prior to each testing session participants were given written instructions to arrive at the laboratory fully hydrated, to have slept for at least 7 h the night before, refrained from the consumption of alcohol, and to have avoided any vigorous exercise 24 h prior to all testing. Participants were also instructed to avoid any caffeine for at least 3 h before each testing session. During sessions two and three participants arrived at the laboratory following an overnight fast. Participants were then provided with a standardized meal that provided 1 g per kg of body weight of carbohydrate. The meal consisted of Special K cereal (Kellogg's co., Michigan, USA) and semi-skimmed milk and participants were required to consume the meal within 15 min. Each treatment began 5 min following breakfast, and all testing sessions were conducted at the same time of day for each individual. Prior to beginning testing, participants were asked to complete a pre-test checklist to ascertain that they had complied with the instructions given to them. Participants were also asked to declare if they had taken any medication/drug or had any acute illness, injury, or infection. Participants completed all testing sessions over a maximum of three weeks with a minimum of 24 h recovery between sessions.

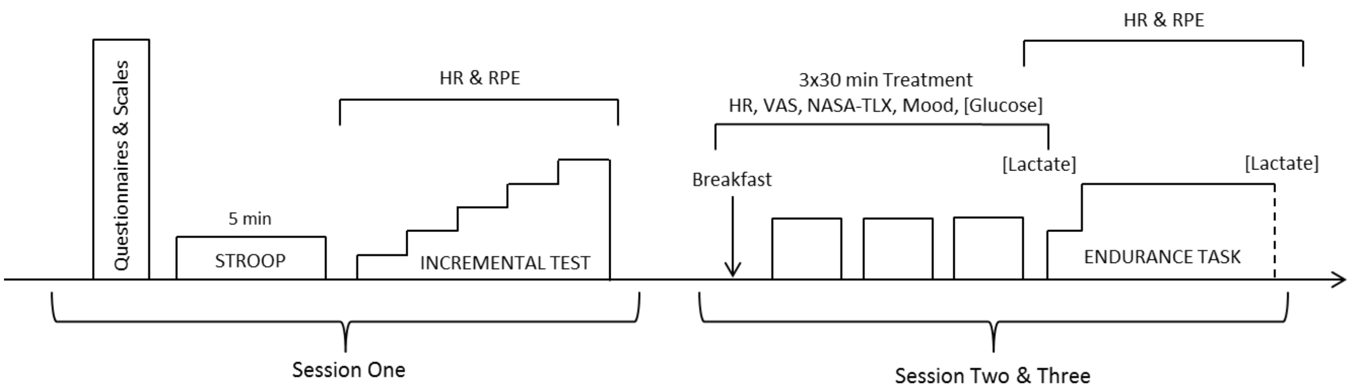

Figure 5.1 Schematic of the experimental protocol. HR: Heart rate. RPE: Rating of perceived exertion. VAS: Visual analogue scale. NASA-TLX: The National Aeronautics and Space Administration Task Load Index rating scale

Mental Exertion Task

The mental exertion task consisted of 90 min performance of a modified incongruent version of the Stroop colour-word task, completed in 3x30 min blocks. Performance of this cognitive task has previously resulted in mental fatigue and impaired endurance performance in recreational runners (Pageaux, Lepers et al. 2014). Participants performed this task at a computer, whilst sitting comfortably in a quiet room. During this task, four words (yellow, blue, green, red) were serially presented on the computer screen, displayed until the participant validated an answer, followed by a 1.5 s rest interval. Participants were instructed to press one of four coloured buttons on the keyboard (yellow, blue, green, red), with the correct response being the button corresponding to the ink colour (either yellow, blue, green, red) of the word presented on the screen. For example, if the word blue appeared in yellow ink, the yellow button had to be pressed. If, however, the ink colour was red, the button to be pressed was the button linked to the written word, not the ink colour (e.g. if the word blue appears in red, the button blue was to be pressed). If the ink colour was blue, green or yellow, then the correct button pressed matched the ink colour. The word presented and its ink colour was randomly selected by the computer. Twenty practice attempts were allowed to ensure the participant fully understood the instructions. The mental exertion task was also performed for 5 min during the initial testing session. Participants were instructed to respond as quickly and accurately as possible. Visual feedback was given after each word in the form of correct or incorrect answer, response speed and accuracy. Mean reaction time, accuracy and number of correct responses were calculated for each 5 min block throughout the 90 min task. Overall reaction time, accuracy and number of correct responses were calculated for the entire task.

Control Task

The control task consisted of watching Earth, a documentary following the migration paths of four animal families (Alastair Fothergill and Mark Linfield, 2007) for a total of 90 min, in 3x30 min blocks in front of the same computer screen used for the mental exertion task. Identical to the mental exertion task subjective manipulation checks were conducted at the end of each 30 min block. This control task has also be been used previously as a non-fatiguing control task in studies of mental fatigue (Pageaux, Marcora et al. 2013).

Physical Performance

An incremental exercise test was completed during the initial testing session in order to determine maximum oxygen uptake and peak power output. The test began at 50 W and was increased incrementally by 50 W every 2 min until exhaustion. Exhaustion was defined as a pedal frequency of less than 60 rpm for more than 5 s despite strong verbal encouragement. Prior to beginning, the position of the cycle ergometer was adjusted for each participant, and settings were recorded so they could be reproduced at each subsequent visit. All physical testing was completed on an electromagnetically braked cycle ergometer (High Performance, Schoberer Rad MeBtechnik, Germany). The cycle ergometer was set in hyperbolic mode, which allows the power output to be set independently of pedal frequency over the range of 30-120 rpm. Maximum oxygen uptake was recorded as the highest oxygen consumption measured during the last minute of incremental exercise test. Oxygen consumption was recorded Peak power output (PPO) was calculated as the highest power recorded during the incremental exercise test and was determined according to the equation; PPO=Wcom + (t/tstage*W), where Wcom represents the highest wattage output that the participant was able to maintain for a complete stage, t is the amount of time in seconds completed in the unfinished stage, tstage is the stage duration, and W is the wattage increase during the unfinished stage (Kuipers, Verstappen et al. 1985).

The endurance task was performed during testing sessions two and three. The task consisted of a 3 min warm up at 40% of PPO followed by a workload corresponding to 80% PPO. Time to exhaustion was measured from the start of the high-intensity workload until the pedal frequency was less than 60 rpm for more than 5 s, or the participant stopped pedaling. Participants were unaware of any of their physiological responses (e.g. heart rate), or the exact time elapsed. Ratings of perceived exertion (RPE) was recorded at the midway point of the warm-up and after each minute of the endurance task using the Borg 6-20 scale (Borg 1970). The term perceived exertion was defined as "the conscious sensation of how hard, heavy, and strenuous exercise is", and all participants were familiar with the scale. RPE was rated on a large scale placed in front of the participant at the appropriate time point. RPE values were anchored using the statements "maximal exertion corresponds to the highest effort you have ever experienced" and "no effort at all corresponds to resting, exerting no effort whatsoever" (Pageaux 2016). This performance task was chosen as it has previously been shown to be sensitive to changes in endurance performance with mental fatigue (Marcora, Staiano et al. 2009). The change in time to exhaustion between interventions was calculated in seconds. The change in endurance performance between interventions was used as a measure of tolerance to mental fatigue. The procedures for sessions two and three were identical apart from the intervention undertaken.

Manipulation Checks

The following measures were recorded throughout the mental exertion and control tasks to determine whether mental fatigue was achieved. Heart rate was recorded at baseline and every 5 min throughout both tasks via a heart rate monitor fitted by a chest strap (T34 Non-Coded Heart Rate transmitter, Polar, Finland). The National Aeronautics and Space Administration Task Load Index (NASA-TLX) rating scale was used to assess subjective workload after each 30 min block of the tasks (Hoonakker, Carayon et al. 2011). The NASA-TLX is composed of six subscales, and four were completed in the present study; mental demand (How much mental and perceptual activity was required?), physical demand (How much physical activity was required?), temporal demand (How much time pressure did you feel due to the rate or pace at which the task occurred?) and effort (How hard did you have to work to accomplish your level of performance?). Participants were asked to score each of the items on a scale divided into 20 equal intervals anchored by the bipolar descriptors high and low. This score was multiplied by 5, resulting in a final score between 0 and 100 for each of the subscales. Subjective ratings of overall fatigue and motivation to complete the endurance task were recorded at baseline and then at the completion of each 30 min block of the tasks using a visual analogue scale (VAS). Participants were required to mark along a 200 mm horizontal line their overall sensation of fatigue, anchored by the statements ‘no fatigue at all’ on the far left and ‘maximal fatigue’ on the far right, and ‘no motivation at all’ on the far left and ‘maximal motivation’ on the far right. Distance from the beginning of the line on the far left was recorded in millimeters.

Lifestyle Behaviours

The simple sports score component of the Baecke questionnaire (Baecke, Burema et al. 1982) was used to determine the physical training load of each participant. Participants were asked to report their two most frequent physical activities in regards to the intensity of the activity, and the number of months per year and hours per week of participation in that activity. A numerical value is assigned to low, medium and high-intensity, as well the numbers of hours per week the activity is participated in, and the number of months per year. From these values participants can achieve a score ranging from 0, indicating the participant does not partake in any regular physical activity, up to a maximum score of 14.58 indicating participation in two activities of high intensity, for >4 h per week each, and >9 months of the year.

The Demand Induced Strain Compensation (DISC) questionnaire was used to quantify the cognitive and emotional occupational load of each participant (van de Ven, Vlerick et al. 2008, van den Tooren and de Jonge 2008). Participants were instructed to ‘suppose someone else (employee X) has the same job in the organization as you have. The tasks, clients, colleagues, supervisors and everything else is identical to your job. Employee X has the same qualifications, training, skills and experience as you for this job. Estimate what the work would be like for employee X’. Each item was in the form of a statement, for example, ‘Employee X will receive information from others (e.g. colleagues and supervisors) in solving complex tasks’ and ‘Employee X will have the opportunity to vary complex tasks with simple tasks’. Each of the 22 items was rated on a 5 point scale five (1 = never or very rarely, 2 = rarely, 3 = occasionally, 4 = often, 5 = very often or always). Each item was described as either a cognitive or emotional resource or demand. An example of a cognitive demand includes needing to make complex decisions at work; an example of an emotional demand includes having to deal with people (e.g. clients, colleagues or supervisors) who have unrealistic expectations. An example of a cognitive resource includes having access to useful information (from computers, books, records, colleagues and operating instructions) to help solve complex tasks, an example of an emotional resource includes other people (e.g. clients, colleagues or supervisors) being a listening ear for employee X when he/she has faced a threatening situation. Overall occupational cognitive and emotional load was calculated as the total score for cognitive demand, minus the total score for cognitive resources, and the total score for emotional demand, minus the total score for emotional resources. A positive value indicates a high occupational cognitive and/or emotional load. A negative value indicates a low occupational cognitive and/or emotional load. At the time of participation all participants were taking part in either full-time employment or study. The lifestyle characteristics of the participants are reported in Table 5.1.

Participant Characteristics	**Mean**	**SD**
Physical Training Load (0 to 14.58)	+5.0	2.9
Cognitive Load (-20 to 20)	-1.4	3.6
Emotional Load (-24 to 24)	-8.8	4.8
Cardiorespiratory Fitness ($ml \cdot kg \cdot^{-1} min^{-1}$)	48.1	8.8

Table 5.1 Mean and standard deviation (SD) of the self-regulatory lifestyle demands and cardiorespiratory fitness of participants

Statistical Analysis

All of the data is presented as mean ± standard deviation. Assumptions of statistical tests such as normal distribution and sphericity of data were checked as appropriate. Greenhouse-Geisser correction to the degrees of freedom was applied when violations to sphericity were present.

For each manipulation check, condition x time repeated measures ANOVAs were used to determine interactions and differences between mental exertion and control tasks. To determine if the manipulation influenced time to exhaustion during the endurance task, a paired t-test was used to compare interventions. A condition x time repeated measures ANOVA was used to compare RPE during the warm-up and first 3 min of the endurance task between interventions. The first 3 min was chosen to include all participants in the analysis. A paired t-test was used to compare RPE at the termination of the endurance task between interventions.

The impact of physical training load, occupational cognitive load, occupational emotional load and cardiorespiratory fitness on cognitive performance and endurance performance were assessed using backward elimination multiple regressions, to determine the smallest number of lifestyle factors which predict the greatest amount of variance in cognitive and endurance performance.

Significance was set at 0.05 for all analyses. Effect sizes for the repeated measures ANOVAs were calculated as partial eta squared (η^2p), using the small=0.02, medium=0.13 and large=0.26 interpretation (3). Effect sizes for the paired t-tests were calculated as Cohen's d (d) using the small=0.2, medium=0.5, large=0.8 interpretation (Cohen 1988). All data analysis was conducted using the statistical packages for social science (SPSS version 20). Due to technical problems with the cycle ergometer, three (2 males, 1 female) of the participants' data collected during the endurance task was not properly recorded. The data for these participants is included in the cognitive performance section only.

5.5 Results

Manipulation Checks

All participants reported to be in good health and were not taking medication at the time of the study. Heart rate was significantly higher during the mental exertion intervention (average heart rate in the mental exertion condition: 72 ± 11 vs control condition: 66 ± 9 bpm, $p<0.001$, $\eta^2p=0.460$), and changed over time during both interventions ($p=0.020$, $\eta^2p=0.106$) (Figure 5.2). Mental demand, physical demand, temporal demand and effort were rated as higher during the mental exertion intervention compared to the control intervention (Table 5.2). Subjective fatigue was not different between interventions at baseline (mental exertion: 6.3 ± 3.7 vs control: 6.4 ± 4.1, p=0.375, $\eta^2p=0.034$), but was higher during the mental exertion intervention at 30 (mental exertion: 8.6 ± 4.2 vs control: 5.7 ± 4.1, p<0.001, $\eta^2p=0.440$), 60 (mental exertion: 9.2 ± 4.5 vs control: 6.4 ± 3.9, p=0.008, $\eta^2p=0.266$) and 90 min (mental exertion: 9.8 ± 4.3 vs control: 6.5 ± 4.1, p<0.001, $\eta^2p=0.492$). Subjective fatigue also increased over time throughout the mental exertion intervention (p<0.001, $\eta^2p=0.439$) but did not change during the control intervention (p=0.492, $\eta^2p=0.028$). Motivation was not different between interventions at any time point (mental exertion p=0.166, $\eta^2p=0.082$), but reduced over time throughout both interventions (p=0.008, $\eta^2p=0.423$). RPE during the endurance task was not higher in the mental exertion condition compared to the control condition (p=0.245, $\eta^2p=0.067$), but did increase over time (p<0.001, $\eta^2p=0.934$). However, to compare RPE values between all participants and the range in time to exhaustion, only the first 3 mins of the endurance task were analyzed. It is possible that a change in RPE was missed in the participants who performed the endurance task for longer than 3 minutes. RPE at exhaustion was not different between interventions (mental exertion: 19±1 vs control: 19±1p=0.110, d=0.287).

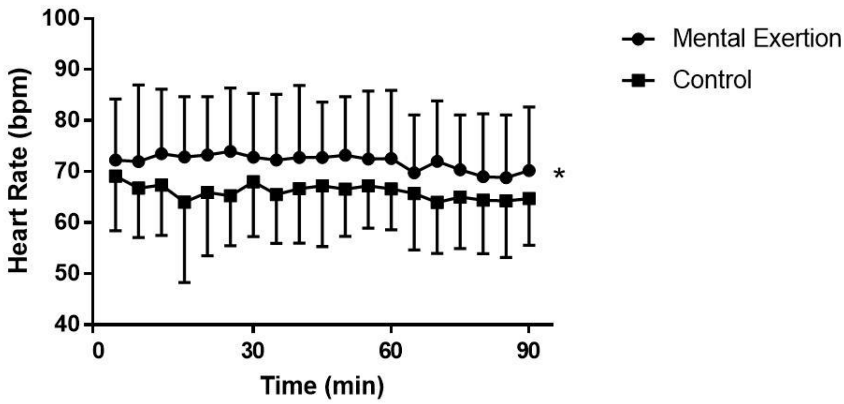

Figure 5.2 Mean heart rate during mental exertion and control interventions. * Significant main effect of condition (p<0.001). Datum is presented as mean ± SD.

	30 min		60 min		90 min	
	ME	CON	ME	CON	ME	CON
Mental Demand (0-100)	59 ± 26*	17 ± 11	62 ± 27*	12 ± 10	66 ± 28*	10 ± 9
Physical Demand (0-100)	54 ± 55^	7 ± 5	18 ± 15*	6 ± 5	21 ± 19^	6 ± 7
Temporal Demand (0-100)	49 ± 23*	8 ± 7	45 ± 22*	6 ± 5	42 ± 22*	6 ± 7
Effort (0-100)	64 ± 20*	10 ± 13	23 ± 9*	7 ± 8	63 ± 24*	8 ± 11

Table 5.2 Subjective workload using the NASA-TLX for the mental exertion and control intervention. Data is presented as mean ± SD. Significant effect of condition *p<0.001, ^p=<0.010

Self-regulatory lifestyle demands, cardiorespiratory fitness and cognitive performance

A multiple regression was run to predict cognitive performance from the lifestyle behaviours of physical training load, occupational cognitive load, occupational emotional load, as well as the physiological variable cardiorespiratory fitness. Physical training load and occupational cognitive demand significantly predicted mean reaction time during the Stroop task (p=0.028, adj. R^2=0.232). Reaction time could be predicted using the equation: reaction time = 934.06 – 14.23 (cognitive load) – 18.60 (training load). Regression coefficients and standard errors for this model are found in Table 5.3. The lifestyle behaviours did not predict accuracy, number of errors or the number of correct responses during the Stroop task.

Lifestyle Factor	B	SE_B	β	p
Intercept	934.062	49.299		
Cognitive Load	-14.230	6.505	-0.414	0.041
Training Load	-18.603	8.179	-0.430	0.034

Table 5.3 Summary of multiple regression analysis predicting mean reaction time during the Stroop task from cognitive load and physical training load. B=Unstandardized regression coefficient. SE_B=Standardised error of the coefficient. Β=Standardised Coefficient. p=statistical significance.

Self-regulatory lifestyle demands, cardiorespiratory fitness and endurance performance

Cycling time to exhaustion was shorter following the mental exertion intervention compared to control (mental exertion: 633±232 vs control: 682±242 s, p=0.049, d=0.207). Fourteen of twenty one participants cycled for a shorter duration of time when mentally fatigued. The range in time to exhaustion in the mental exertion condition was 259-1241 s and 288-1241 in the control condition. A multiple regression was run to predict the change in time to exhaustion between mental exertion and control interventions from physical training load, occupational cognitive demand, occupational emotional demand and cardiorespiratory fitness. Occupational cognitive load, physical training load and cardiorespiratory fitness significantly predicted change in time to exhaustion ($p=0.005$, adj. $R^2=0.456$). Change in time to exhaustion between the mental exertion and control condition could be predicted using the equation: Δ time to exhaustion = 125.24 + 8.46 (cognitive load) + 9.75 (training load) – 3.80 (fitness). Regression coefficients and standard errors for this model are found in Table 5.4.

Lifestyle Factor	B	SE_B	β	p
Intercept	125.241	71.285		
Cognitive Load	8.456	3.737	0.403	0.038
Training Load	9.751	4.275	0.422	0.037
Aerobic Fitness	-3.799	1.568	-0.457	0.028

Table 5.4 Summary of multiple regression analysis predicting change in time to exhaustion between mental exertion and control interventions. B=Unstandardized regression coefficient. SEB=Standardised error of the coefficient. β =Standardised Coefficient. p=statistical significance

5.6 Discussion

The aim of the present study was to determine whether self-regulatory lifestyle demands and/or cardiorespiratory fitness are associated with (a) inhibitory control and (b) resistance to mental fatigue. It was determined that physical training load and occupational cognitive load predicted 23.2% of the variance in mean reaction time during the inhibitory control task. The greater one's physical training load and occupational cognitive load, the faster their mean reaction time. Physical training load, occupational cognitive load and cardiorespiratory fitness predicted 47.0% of the variance in the change in time to exhaustion between the mental exertion and control interventions. Greater physical training load and occupational cognitive load were associated with better maintenance of endurance performance when mentally fatigued. A higher level of cardiorespiratory fitness was associated with worse endurance performance following mental exertion. The finding that cardiorespiratory fitness was negatively associated with mental fatigue resistance was surprising, and cannot be fully explained in this paper. Combined, these findings suggest that participation in both cognitive and physical exertion may help improve self-regulation, and thus tolerance to mental fatigue. It may also be suggested that participation in self-regulatory activities may be more beneficial than the physiological adaptations themselves.

Mental fatigue was successfully induced and endurance performance was impaired following 90 min performance of the modified Stroop task. Subjective measures of mental fatigue and average heart rate were higher during the mental exertion intervention compared to the control intervention reflecting the greater cognitive effort of the task (Richter, Friedrich et al. 2008). Physical training load and occupational load were able to predict mean reaction time during the Stroop task, but none of the self-regulatory lifestyle demands predicted either accuracy, number of errors, or number of correct responses. A positive effect of exercise on cognition and brain health has been reported previously. Aerobic exercise is associated with improvements in both general executive functioning (Smith, Blumenthal et al. 2010) and incongruent Stroop task performance (Smiley-Oyen, Lowry et al. 2008), and grey and white matter volume in the prefrontal cortex of older adults was increased with a 6 month aerobic exercise program (Colcombe, Erickson et al. 2006). Reaction time has shown to improve following an aerobic training intervention in older adults (Dustman, Ruhling et al. 1984, Baylor and Spirduso 1988) and physical activity levels were strongly and positively correlated with academic results in primary school aged children (Telford, Cunningham et al. 2012). The finding that greater occupational cognitive load is associated with better cognitive performance in a task of inhibitory control is novel. Nevertheless, practice of one task of self-regulation has been shown to improve self-regulation on another, unrelated task (Oaten and Cheng 2004a, Oaten and Cheng 2006, Oaten and Cheng 2007). These results suggest that regularly persisting with a task requiring self-regulation, whether physical or cognitive, may improve more general self-regulatory capacity.

Physical training load, occupational cognitive load and cardiorespiratory fitness were predictive of the change in time to exhaustion between the mental exertion and control interventions. A higher physical training load and greater occupational cognitive load were associated with better maintenance of endurance performance when mentally fatigued. Although this is the first study to examine the effect of occupational cognitive load on both cognitive and physical performance when mentally fatigued, it has previously been shown that the addition of a cognitive task performed concurrently with a 12 week cycling training program improved cycling time to exhaustion to a greater extent than the cycling program alone (Marcora, Staiano et al. 2015). Both that study and the current study support the strong transfer effect of improvement in one type of self-regulation to that of another (Muraven, Baumeister et al. 1999, Oaten and Cheng 2004a). The positive relationship demonstrated by physical training load and occupational training load, with both cognitive and endurance performance when mentally fatigued suggests that self-regulatory mechanisms adapt in a response to training or stimulus intensity and/or duration (Dudley and Terjung 1982, Demirel, Powers et al. 1999). The findings of this study support that a more physically and cognitively demanding lifestyle might provide more of a training stimulus for improved self-regulation than a less physically and cognitively demanding lifestyle.

In contrast to physical training load, a higher level of cardiorespiratory fitness, determined by maximal oxygen consumption, was associated with worse endurance performance when mentally fatigued. Maximal oxygen consumption is strongly determined by genetics (Leitch, Clancy et al. 1975), although it can be improved with training (Leitch, Clancy et al. 1975). This means that distinguishing between cardiorespiratory fitness and training load is often problematic, and to attribute an effect to one but not the other is difficult. Physical training load was positively correlated with resistance to mental fatigue, whereas cardiorespiratory fitness was negatively associated to mental fatigue resistance, which may suggest that the behaviours associated with attempting to improve oxygen uptake (i.e. training load) relate more to superior self-regulation than the improvement in cardiorespiratory fitness itself. Our recent study suggested that the greater resistance to mental fatigue of professional road cyclists could be attributed to greater inhibitory control or self-regulatory capacity of the professional athletes compared to the recreational athletes (Martin, Staiano et al. 2016). This study could not conclude however, whether this greater capacity was due to genetics, the benefits of aerobic exercise on brain structure and function, or greater practice of self-regulatory behaviors (Martin, Staiano et al. 2016). Again, this study was not designed to address such a question; however, these findings do suggest that the behaviors of the professional athletes (maintaining a strict training program, observing dietary restrictions, limiting late nights etc) may have contributed more to their increased resistance to mental fatigue, than any physiological adaptation linked with a high level of cardiorespiratory fitness. Mental fatigue is thought to impair subsequent endurance performance via an increase in RPE, rather than any other physiological or psychological variable (Marcora, Staiano et al. 2009). Continuing to exercise when mentally fatigued, despite an increase in perception of effort, requires an individual to override the urge to quit or slow down (self-regulation). Regular participation in physical activity requires greater self-regulation than the alternative of being inactive. It is plausible that this cognitive decision to be active is of greater benefit in resistance to mental fatigue than the by-product of improved cardiorespiratory fitness. In addition, although maximum oxygen consumption is a strong predictor of endurance performance (Barlow, Weltman et al. 1985) other physiological variables including running economy (Bassett and Howley 1997) and speed at lactate threshold (Farrell, Wilmore et al. 1979) explain a large portion of the variance in performance outcomes. In the population sampled in this study it can be speculated that the participants with high cardiorespiratory fitness, did not necessarily engage in greater amounts of physical activity to maintain their fitness level compared to other participants. In fact, correlation between the number of hours spent engaged in physical activity per week and maximal oxygen consumption was low (R^2=0.068). Likewise, participants who have a lower cardiorespiratory fitness may record a similar physical training load but find the physical activity more challenging, and thus may see greater improvement in self-regulation.

5.7 Practical Applications

This is the first study to investigate whether lifestyle factors, which require self-regulation, mediate both cognitive and physical performance when mentally fatigued. A higher physical training load and a greater occupational cognitive load were associated with a faster reaction time during the mentally fatiguing Stroop task. Similarly, a higher physical training load and a greater occupational cognitive load was associated with better maintenance of endurance performance when mentally fatigued. These findings are promising as they suggest that participation in both cognitive and physical exertion improves self-regulation, and thus tolerance to mental fatigue. In a practical sense, both of these factors may be used within an intervention for those susceptible to performance decrements with mental fatigue, as well as other individuals who suffer from issues with self-control. Given that physical training load and occupational cognitive load appear to facilitate self-regulation, as well as the evident transfer of improvement of self-regulation between unrelated tasks, future research should focus on the efficacy of a cognitive and physical training intervention on other applications of mental fatigue and reduced self-regulation or self-control. It is also important that future research focuses on the physiological or psychological mechanisms behind the improvement in cognitive and physical performance with increase in self-regulatory capacity.

5.8 Conclusion

This is the first study to investigate whether self-regulatory lifestyle demands and/or cardiorespiratory fitness are associated with (a) inhibitory control and (b) resistance to mental fatigue. Higher physical training load and greater occupational cognitive load were associated with greater inhibitory control, as well as better maintenance of endurance performance when mentally fatigued. These findings are promising as they suggest that participation in both cognitive and physical exertion may improve self-regulation, and thus tolerance to mental fatigue. The negative relationship between cardiorespiratory fitness and resistance to mental fatigue may suggest that the improved self-regulation related to physical activity participation may be more beneficial than the cardiorespiratory benefits gained from the exercise itself. Interventions utilizing combined cognitive and physical exertion should be trialed as a way to reduce performance decrements in those susceptible to mental fatigue, as well as improve self-regulation in those with low self-regulatory control.

Chapter Six: Mental Fatigue Impairs Endurance Performance: A Physiological Explanation

Declaration for Thesis Chapter Six

In the case of Chapter Six, Kristy Martin contributed to the literature review and preparation of the manuscript, the extent of this contribution was 80%.

The following co-authors also contributed to the work; Ben Rattray (preparation of manuscript), Romain Meeusen (preparation of manuscript), Richard Keegan (preparation of manuscript) and Kevin Thompson (preparation of manuscript). None of the co-authors are students.

Candidate's signature ___________________________ **Date** ____________________

Declaration by co-authors

The undersigned hereby certify that:

1. The above declaration correctly reflects the nature and extent of the candidate's contribution to this work, and the nature of the contribution of each of the co-authors

2. They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise

3. They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication

4. There are no other authors of the publication per these criteria

5. Potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit

6. The original data is stored at the University of Canberra Research Institute for Sport and Exercise and will be held for at least five years

Ben Rattray **Date:** 09·11·2016

Romain Meeusen **Date:** 09·11·2016

Richard Keegan **Date:** 09·11·2016

Kevin Thompson **Date:** 09·11·2016

6.1 Foreword

The following chapter is a theoretical review designed to combine the findings of the previous three chapters, as well as the findings of others who completed mental fatigue and physical performance research concurrently with this thesis. The following chapter uses this combined knowledge to propose a physiological mechanism for the increase in rating of perceived exertion and worse endurance performance of mentally fatigued participants. This chapter also discusses a plausible explanation for the apparent increased tolerance to mental fatigue of professional athletes. Evidence is drawn from studies in other modes of fatigue (i.e. sleep deprivation), as well as in vitro and animal studies. The basis of the proposed hypothesis is a reduction in cerebral fuel stores, instigated by prolonged mental exertion that causes a change in the concentration of other neurotransmitters in the brain, which in turn produce psychological and physiological effects, thereby impairing performance.

6.2 Abstract

Mental fatigue is a change in psychobiological state caused by prolonged periods of demanding cognitive activity. It is known that mental fatigue impairs cognitive performance, however, more recently it has been observed that mental fatigue also impairs endurance performance.

The mechanism behind the negative effect of mental fatigue on endurance performance is poorly understood with variables traditionally believed to limit endurance performance such as heart rate, lactate accumulation and neuromuscular function unaffected by mental fatigue. Rather, it is suggested that mental fatigue impairs endurance performance via an increase in perception of effort. Prolonged mental exertion is thought to increase cerebral extracellular concentrations of adenosine and this accumulation is thought to be responsible for greater perceived exertion during exercise. Experimental evidence has shown that neural activity increases extracellular adenosine, that adenosine induces a reduction in endurance performance, and that caffeine, a potent adenosine antagonist both reduces perceived exertion and improves endurance performance.

This brief review presents the hypothesis that physiological changes within the brain instigate the increase in perceived exertion and reduced endurance performance observed when mentally fatigued. We propose cerebral fuel stores are consumed with mental exertion and reduced availability of fuel increases accumulation of adenosine. We suggest adenosine's effect is two-fold; to increase perceived exertion and moderate motivation via its interaction with dopamine receptors. Finally we propose that similar to muscle, supercompensation of cerebral fuel stores occur with adequate recovery following physical and mental exertion induced cerebral fuel depletion. Increased cerebral fuel stores would reduce extracellular adenosine and may provide a level of tolerance to performance decrements associated with mental fatigue.

Mental Fatigue Impairs Endurance Performance: A Physiological Explanation

6.3 Introduction

Mental fatigue reflects a change in psychobiological state, caused by prolonged periods of demanding cognitive activity (Marcora, Staiano et al. 2009). This change is gradual and cumulative and has subjective and objective manifestations including increased resistance against further effort, changes in mood and feelings of 'tiredness' and 'lack of energy'. It has been well documented that mental fatigue impairs cognitive performance (van der Linden, Frese et al. 2003, Boksem, Meijman et al. 2005, Lorist, Boksem et al. 2005), however, only recently has it been demonstrated that aspects of physical performance are also impaired by mental fatigue (Marcora, Staiano et al. 2009, MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014, Smith, Marcora et al. 2014, Smith, Coutts et al. 2015). Time to exhaustion during both high-intensity cycling (Marcora, Staiano et al. 2009) and a sustained isometric leg extension (Pageaux, Marcora et al. 2013) were reduced following a mentally fatiguing task, and average running speed was slower during a 5 km treadmill (Pageaux, Lepers et al. 2014) and a 3 km track running time trial (MacMahon, Schücker et al. 2014). Other measures of physical performance have also been impaired with mental fatigue, such as the low intensity component of an intermittent running protocol (Smith, Marcora et al. 2014), and the performance of the Yo-Yo Intermittent Recovery test (Smith, Coutts et al. 2015). An exception to the consistent reporting of a reduction in endurance performance with mental fatigue is the unaffected time trial performance of professional road cyclists following 30 min of mental exertion (Martin, Staiano et al. 2016). In this study, professional and competitive recreational cyclists were exposed to an identical cognitive task and experimental procedures. During the performance of a subsequent cycling time trial, and consistent with the literature, the recreational cyclists recorded a lower mean power output and a slower average speed in the mental exertion condition, whereas the endurance performance of the professional cyclists was unchanged between mental exertion and control conditions (Martin, Staiano et al. 2016). Although the mental fatigue manipulation may seem short, 30 min performance of the same cognitive task has also impaired time trial performance in recreational runners (Pageaux, Lepers et al. 2014).

Mental Fatigue and Endurance Performance

The mechanism behind the detrimental effect of mental fatigue on endurance performance is poorly understood. Variables traditionally believed to limit endurance performance, such as heart rate, lactate accumulation, peripheral fuel availability and neuromuscular function have been found to be unaffected by mental fatigue (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013). Rather, it has been suggested that the negative impact of mental fatigue on endurance performance is due to the greater rating of perceived exertion (RPE) experienced by mentally fatigued participants (Marcora, Staiano et al. 2009). In a time to exhaustion task the impact of a higher RPE is demonstrated by participants reaching a terminal RPE more quickly and disengaging from a task earlier (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013). In a time trial setting the average power output or speed able to be produced for the same RPE is lower (MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014). In 2014, Pageaux and colleagues proposed that prolonged performance of a demanding cognitive task increases cerebral adenosine accumulation and that this accumulation may lead to the higher perception of effort experienced during subsequent endurance performance. Experimental evidence from both in vitro and animal studies suggests that neural activity increases extracellular adenosine (Pull and McIlwain 1973, Lloyd, Lindström et al. 1993) and reduces exercise time to exhaustion in rats (Davis, Zhao et al. 2003). Caffeine, a potent adenosine antagonist, also both reduces RPE and improves endurance performance in humans (Doherty and Smith 2005). One of the areas in which adenosine is hypothesised to accumulate during prolonged mental exertion is the anterior cingulate cortex (ACC). The ACC is strongly activated during tasks of inhibitory control such as the Stroop task and the Continuous Performance task AX version (Barch, Braver et al. 1997, Carter, Braver et al. 1998). These cognitive tasks are employed regularly within the literature to induce mental fatigue (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013, Pageaux, Lepers et al. 2014, Smith, Marcora et al. 2014). In addition, changes in the activation of the ACC correlate with changes in RPE during manipulations of exercise intensity under hypnosis and motor imagery (Williamson, McColl et al. 2001) and rats with experimental ACC lesions were reported to engage significantly less in tasks requiring physical effort to obtain a larger reward (Rudebeck, Walton et al. 2006).

As briefly outlined in figure 6.1, this theoretical review presents the hypothesis that there is a physiological explanation behind the increase in RPE and impaired endurance performance when mentally fatigued. We propose that prolonged and demanding mental exertion consumes cerebral glucose and glycogen to a greater extent than during a less demanding task or while at rest. During periods of demanding mental exertion adenosine accumulates within active regions of the brain, as a result of increased neural activity and reduced fuel availability. Greater levels of adenosine impair subsequent endurance performance via an increase in RPE and antagonism of dopamine, reducing motivation and further impacting endurance performance. While this review focuses on the role of the ACC, glycogen, adenosine and dopamine in the impact of mental fatigue on endurance performance, it is certain that other neural structures and regions, fuel sources, neurotransmitters and peripheral mechanisms are also involved. However, by narrowing our focus on these particular facets we are able to present our view on what is a central aspect of this important and complex psychophysiological phenomenon.

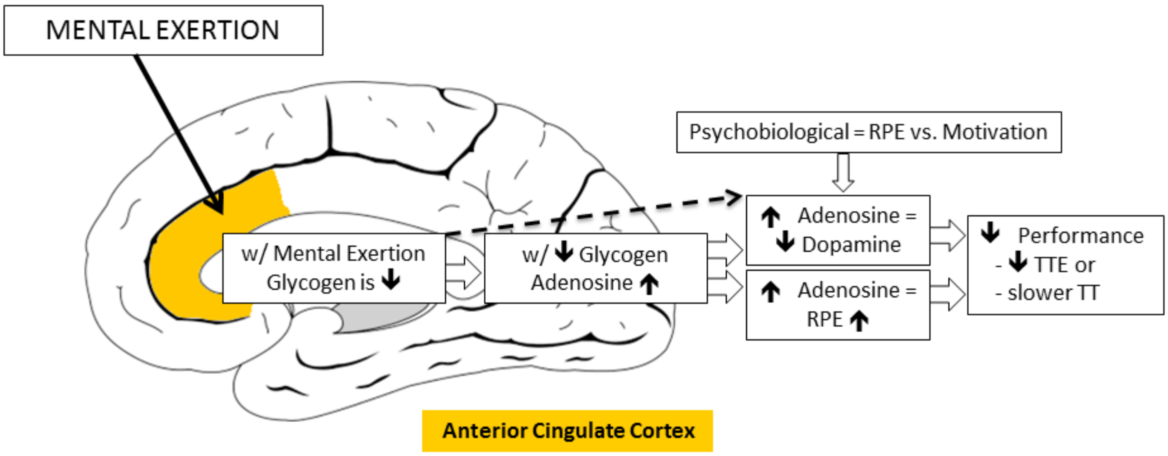

Figure 6.1 Schematic of the hypothesised physiological mechanism for negative effect of mental fatigue on endurance performance

6.4 Glycogen

Glucose is stored in the brain as glycogen in the astrocytes (Wender, Brown et al. 2000) and can be degraded in response to sudden increases in energy demand including both periods of increased neuronal activity (Brown and Ransom 2007) and prolonged endurance exercise (Matsui, Soya et al. 2011). The turnover of glycogen in the brain is rapid, thus, astrocytic glycogen is not a passive store but is likely to make a substantial contribution to energy metabolism during neuronal activation (Dienel, Wang et al. 2002). Although glucose and glycogen are the primary fuel source of the brain, it has been recently proposed that other fuel sources, such as lactate, can contribute to fuelling brain activation. In the resting brain, nearly all of the glucose metabolised within neurons is oxidised (Ames 2000) however, during periods of high brain activation, astrocytes metabolise glucose forming lactate as a by-product (Todd 2014). Neuronal efflux of lactate is facilitated by monocarboxylate transporter 4, which releases lactate into the interstitial fluid. Lactate is then transported into neurons, via monocarboxylate transporter 2, where it is enzymatically converted into pyruvate by lactate dehydrogenase. Pyruvate then enters the citric acid cycle within astrocyte mitochondria, contributing to the oxidative adenosine triphosphate (ATP) yield (Draoui and Feron 2011). Neurons therefore can source lactate directly from astrocytes, consuming cerebral fuel stores, but also via the bloodstream (Boumezbeur, Peterson et al. 2010). During exercise when blood lactate concentration increases several fold, the human brain additionally takes up and metabolizes exogenous lactate (Ide, Schmalbruch et al. 2000). Despite these recent observations, lactate and other sources of energy are regarded as a supplementary fuel source and glucose and glycogen remains the major energy source of the brain (Boumezbeur, Peterson et al. 2010). For this reason, the remainder of this review will focus on glucose and glycogen as the brains primary fuel source.

Mental Exertion Consumes Brain Glucose and Glycogen

Cerebral fuel stores are consumed with any cognitive process, however, those processes requiring greater cognitive effort, such as executive functioning or self-regulation are believed to be more metabolically expensive and require larger amounts of energy to function optimally compared to other cognitive capacities (Gailliot and Baumeister 2007). The performance of a demanding cognitive task, compared to a less demanding cognitive task, is associated with greater activation of certain areas of the brain including the right superior mesial frontal region and the ACC (Pardo, Pardo et al. 1990, Larrue, Celsis et al. 1994). Activation within the prefrontal and parietal cortices have also shown to be sensitive to task difficulty (Grady, Horwitz et al. 1996, Cohen, Perlstein et al. 1997, Jonides, Schumacher et al. 1997). Glycolytic metabolism increases with corresponding increases in brain activity (Figley and Stroman 2011) and decreases in hippocampal extracellular glucose were associated with increasing cognitive demand in rats (McNay, Fries et al. 2000). Decreased neuronal activity, as observed during sleep and anesthesia, also correlates with increased levels of brain glycogen (Watanabe and Passonneau 1973, Karnovsky, Reich et al. 1983).

Given the technical difficulty of measuring the glucose consumed within the human brain, peripheral blood glucose concentration is routinely reported as an approximate substitute. The use of peripheral blood glucose concentration is supported by positive correlations between both brain glucose and glycogen levels, and peripheral blood glucose concentration in exercising rats (Matsui, Soya et al. 2011). In human studies, peripheral blood glucose concentration has shown to be sensitive to both time on task, and task difficulty during mental exertion (Fairclough and Houston 2004, Gailliot, Baumeister et al. 2007). However, it has also been argued that task-induced changes in human peripheral blood glucose are unlikely to reflect changes in relevant areas of brain glucose supply (Messier 2004). In support of this argument, many studies have not been able to replicate a reduction in peripheral blood glucose concentration with increasing mental exertion, including studies of mental fatigue and physical performance (Marcora, Staiano et al. 2009, Pageaux, Lepers et al. 2014, Smith, Marcora et al. 2014). The authors tend to agree with these arguments and suggest that studies utilizing peripheral blood glucose concentration as a marker of cerebral fuel stores, in the context of mental fatigue, offer very weak, or perhaps no relevance at all.

In this review, we propose that brain glucose and glycogen is consumed during prolonged periods of demanding cognitive activity, and to a greater extent when performing a more demanding task compared to a less demanding task. In comparison to the liver or skeletal muscle, only a small amount of glycogen is stored within the astrocytes (Brown 2004) and therefore the reduction in fuel brought about by performance of a demanding cognitive task may not be large, or necessarily reflected in peripheral circulation. Nevertheless, a small reduction in absolute glycogen concentration in the brain, especially when localized in specific brain areas, is likely to have more substantial consequences. We propose this reduction in cerebral fuel stores, brought about by prolonged demanding mental exertion, will augment an increase in cerebral adenosine and can subsequently increase RPE, reduce motivation and impair endurance performance. The effect of increased adenosine will be discussed in later sections.

The role of glucose in mental fatigue may also not be entirely metabolic. Studies of mouth rinsing suggest that simply the presence of a glucose solution in the mouth can result in improved physical (Chambers, Bridge et al. 2009) and cognitive performance (Sanders, Shirk et al. 2012). The presence of glucose in the oral cavity increases activity in the ACC and the ventral striatum of the brain

(Chambers, Bridge et al. 2009), as well as the orbitofrontal cortex (De Pauw, Roelands et al. 2015). This activation occurs in response to the presence of glucose in the oral cavity but not to an artificially sweetened placebo (Chambers, Bridge et al. 2009). In a more specific sporting context, mouth rinsing with a glucose solution has allowed participants to produce a greater power output for a given workload (Chambers, Bridge et al. 2009). The activation of these reward centres of the brain has been suggested to induce an ergogenic effect on exercise performance by reducing RPE during exercise (Carter, Jeukendrup et al. 2004). Using regions of the brain, such as the ACC, during prolonged mental exertion is likely to reduce cerebral fuel stores, thereby increasing accumulation of adenosine which has an inhibitory effect on the central nervous system (Fredholm, Battig et al. 1999). We believe this will consequently impair subsequent endurance performance, via an increase in RPE and reduction in motivation. Given the positive effect of central stimulants on RPE and endurance performance in non-mentally fatigued participants, future research should investigate the effect of these substances on participants in a mentally fatigued state.

Increasing Cerebral Glycogen with Training

Support for our hypothesis that cerebral fuel stores are implicated in the increase in RPE and impaired endurance performance with mental fatigue may be found in the superior cognitive performance and tolerance to mental exertion of professional road cyclists (Martin, Staiano et al. 2016). During a 30 min Stroop task, professional cyclists completed over 20% more trials correctly than recreational cyclists. In addition, during a subsequent time trial, both RPE and endurance performance of the professional cyclists was unchanged compared to the control condition (Martin, Staiano et al. 2016). During exercise, glycogen is degraded within skeletal muscle in an activity dependent manner, related to exercise intensity and/or duration, and is utilized to supply energy for ATP synthesis (Gollnick, Piehl et al. 1974). At the cessation of exercise, provided sufficient rest and carbohydrate is consumed, restoration of muscle glycogen occurs within 24 hours (Bergström, Hultman et al. 1967). As an adaptation to the increased energy demand of a depleting physical task, muscle glycogen is increased to above basal levels (supercompensation) (Bergstrom and Hultman 1966). Furthermore, regular depleting exercise further increases both the rate and magnitude of muscle glycogen supercompensation after exercise in humans (Greiwe, Hickner et al. 1999) and rats (Nakatani, Han et al. 1997). Similar to that observed within the muscle, glucose utilization in exercising rat brain is increased (Vissing, Andersen et al. 1996) and with prolonged exercise, levels of cerebral glycogen are reduced (Matsui, Soya et al. 2011). Following feeding and recovery, supercompensation of cerebral glycogen is observed 24 h post exercise (Matsui, Ishikawa et al. 2012), and after 4 weeks of regular endurance training, basal cerebral glycogen levels are increased further (Matsui, Ishikawa et al. 2012). Acute cerebral glycogen supercompensation has also been observed in both humans (Öz, Kumar et al. 2009) and rats (Choi, Seaquist et al. 2003) following a single bout of insulin-induced moderate hypoglycemia, suggesting that the human brain has the capacity for adaptation.

In the view that cerebral glycogen stores may supercompensate in response to prolonged physical exertion, we suggest that the greater training volume and intensity of professional road cyclists may induce similar adaptations. Just as with skeletal muscle, it seems probable that the adaptation of cerebral glycogen is relative to the intensity and duration of the physical training bout. In the aforementioned study, the professional cyclists trained for a significantly greater duration per week, as well as completed more high intensity training sessions than the recreational cyclists (Martin, Staiano et al. 2016). Cerebral glycogen supercompensation may also have further been increased due to the mental exertion required to commit to long, individual training rides. This improvement in cognitive and endurance performance would seem likely given that supplementation of glucose has previously improved both cognitive performance (Gonder-Frederick, Hall et al. 1987, Manning, Hall et al. 1990, Benton, Owens et al. 1994, Craft, Murphy et al. 1994, Benton and Parker 1998) and endurance capacity (Coggan and Coyle 1991). We cannot discount of course that adaptations in the cognitive performance of elite performers are also likely through increases in the efficiency of neuronal processing (Ludyga, Gronwald et al. 2016). Increased neuronal efficiency would lead to greater conservation of cerebral fuel, similar to the preservation of skeletal muscle glycogen observed with changes in movement economy (Hawley 2002).

It is possible that prolonged and demanding cognitive exertion may stimulate cerebral fuel supercompensation. This hypothesis is yet to be experimentally tested, however, with certain pathological conditions and following sleep deprivation an increase in cerebral glycogen has been observed (Kong, Shepel et al. 2002, Dalsgaard, Madsen et al. 2006). In patients with temporal lobe epilepsy, a condition characterized by excessive neuronal activity, glycogen content was higher in tissue obtained from pathologic hippocampus compared with ‘normal’ cortical gray and white matter (Dalsgaard, Madsen et al. 2006). Following 12 h of sleep deprivation in which cerebral glycogen stores were reduced, a 15 h recovery sleep increased glycogen levels above baseline levels (Kong, Shepel et al. 2002). Furthermore, although the mechanisms behind the improvement were not examined, 12 weeks of training including the performance of a demanding cognitive task concurrent to a cycling task improved cycling time to exhaustion to a greater extent than cycling training alone (Marcora, Staiano et al. 2015). At the completion of the 12 weeks, there was no difference between groups in typical measures of endurance performance such as maximal oxygen uptake. Rather, improved performance was associated with a slower increase in RPE during the cycling endurance task. Given the greater intensity and likely metabolic demands of the combined physical and mental training program, we believe the combined training program would have provided a particularly strong stimulus for cerebral fuel adaptation.

In this review we look at evidence to support the role of cerebral glucose and glycogen during prolonged and demanding mental exertion (McNay, Fries et al. 2000, Figley and Stroman 2011), and that with the consumption of fuel greater than what is experienced during a less demanding task, or at rest. We suggest that similar to skeletal muscle, the brain is adaptive to the stressors placed upon it and that both endurance exercise and demanding cognitive exertion, may consume fuel stores within the brain, subsequently allowing for supercompensation. A greater supply of cerebral glycogen may facilitate improved cognitive and physical performance, as well as minimize the accumulation of adenosine.

6.5 Adenosine

Adenosine is a cellular component that forms part of ATP. Any manipulation that causes the energy requirements of the brain to outstrip its ability to synthesize ATP greatly increases adenosine release (Dunwiddie and Masino 2001). Adenosine accumulation will therefore occur either through an increase in energy demand or through a reduction in metabolic substrate relative to the demand. Under these conditions, ATP levels are reduced, and the levels of adenosine are increased (Dunwiddie and Masino 2001). Adenosine concentration increases in muscle and plasma during exercise (Davis, Zhao et al. 2003), but also increases progressively in the brain during wakefulness and then decreases during sleep (Huston, Haas et al. 1996). To date, the negative impact of mental fatigue on endurance performance and capacity has been suggested to be attributed to an accumulation of cerebral adenosine, which in turn is believed to contribute to the increase in RPE during subsequent endurance performance (Pageaux, Lepers et al. 2014). Electrical stimulation increases the formation and release of adenosine in rat brain slices (Pull and McIlwain 1973), as can energy depletion (Lloyd, Lindström et al. 1993), moderate hypoglycaemia and glycolytic inhibition (Fowler 1993, Zhu and Krnjevi 1993, Zhao, Tekkök et al. 1997). Performance of a cognitive task increases brain metabolic activity above baseline levels (Phelps 1985, Grafton, Mazziotta et al. 1992), while during anesthesia, brain oxygen and glucose consumption are reduced (Shulman, Hyder et al. 2009). This review presents the hypothesis that prolonged and demanding mental exertion consumes brain glucose and glycogen. With mental exertion accumulation of adenosine is increased, facilitated by the increase in brain activation as well as the reduction in fuel stores. We suggest that adenosine then impairs endurance performance via an increase in RPE and a reduction in motivation.

Adenosine Increases Rating of Perceived Exertion

Adenosine is hypothesized to accumulate during prolonged mental exertion, and contribute to the increase in RPE observed in mentally fatigued participants (Pageaux, Lepers et al. 2014). There has been no direct evaluation of the effect of adenosine on RPE during exercise performance but measurement of adenosine in the forebrain of cats suggests that extracellular concentrations of adenosine progressively increase during prolonged wakefulness and decrease during subsequent recovery sleep (Porkka-Heiskanen 1999). Looking at studies of sleep deprivation and endurance performance, RPE assessed in humans during exercise is increased compared to a control condition, like that observed with mental fatigue. For example, 36 h of sleep deprivation increased RPE and reduced time to exhaustion during prolonged treadmill walking (Martin 1981), and the increases in RPE during treadmill performance appear to be related to the duration of sleep lost (Myles 1985). Distance covered during a self-paced intermittent running protocol was reduced after 30 hours of sleep deprivation (Skein, Duffield et al. 2011) and distance covered in a 30 min running time trial was lower following 30 h without sleep, compared to a normal night's sleep (Oliver, Costa et al. 2009). During these trials RPE was not different between conditions, meaning that a slower running or walking speed was maintained for the same RPE in the sleep deprivation trial compared to the control trial. This is an observation consistent with the physical performance and mental fatigue literature.

Support for adenosine playing a role in the increase in RPE of mentally fatigued participants may also be derived from animal studies. We acknowledge that it is not possible to directly quantify perceived exertion in animals, however, manipulations of adenosine agonists and antagonists profoundly affect effort-related choice behavior and appear to make animals more sensitive to the work requirements of a task. In a feeding procedure in which rats could choose between a physically demanding task requiring a press of a lever for a preferred food or consuming readily available lab chow, systemic injections of an adenosine agonist reduced the number of lever presses for the preferred food, but did not affect overall food intake (Font, Mingote et al. 2008). Intracranial injections of an adenosine agonist reduced total responses to a task requiring a high level of effort to obtain a food reward (Mingote, Font et al. 2008) and administration of an adenosine receptor agonist reduced run time to exhaustion compared to the control conditions, without change in any other variable (Davis, Zhao et al. 2003). In this review, we hypothesize that with prolonged mental exertion cerebral fuel stores are reduced, thereby increasing cerebral adenosine concentration. Adenosine increases RPE during subsequent endurance exercise which impairs performance compared to a non-mentally fatigued state.

Caffeine Counters the Effects of Adenosine

The effect of caffeine on RPE and endurance performance also supports the notion that adenosine contributes to the increased RPE experienced by mentally fatigued participants. Caffeine is a socially acceptable, legal drug consumed by both athletes and the general population. The stimulatory effect of caffeine is believed to stem from its ability to antagonize the actions of adenosine (Dunwiddie and Masino 2001). Caffeine is very similar in structure to adenosine and can bind to cell membrane receptors for adenosine, thus blocking their action (Graham 2001). Caffeine easily crosses the blood-brain barrier due to its lipophilic properties (McCall, Millington et al. 1982) and has been shown to counteract most of the inhibitory effects of adenosine on neuro-excitability (Fredholm, Battig et al. 1999), neurotransmitter release (Okada, Kiryu et al. 1997), arousal (Porkka-Heiskanen 1999), and spontaneous activity (Barraco, Coffin et al. 1983). In an exercise context, ingestion of caffeine increased total work performed when participants were asked to cycle at a given intensity, when compared to a placebo (Cole, Costill et al. 1996). Similarly, caffeine increased power output and reduced RPE during a high-intensity cycling bout in trained cyclists (Doherty, Smith et al. 2004) . In sleep-deprived participants, caffeine reduced RPE and improved time to exhaustion back to baseline levels (McLellan, Bell et al. 2004), as well as maintained cognitive performance (Penetar, McCann et al. 1993). Caffeine has also been reported to improve alertness and mood (Wesensten, Belenky et al.

2002), and combined caffeine and carbohydrate ingestion has been reported to lessen subjective mental fatigue during prolonged mental exertion (Kennedy and Scholey 2004). More specifically, the ingestion of caffeine prior to 90 min of mental exertion also improved cycling time to exhaustion compared to the ingestion of a placebo, or nothing (Azevedo, Silva-Cavalcante et al. 2016). In this study, cardiorespiratory, metabolic and neuromuscular variables were not different between conditions, nor was RPE at the end of the task. Maintenance of vigour and a reduction in subjective fatigue with caffeine ingestion was suggested to underlie the improved endurance performance in a state of mental fatigue. The use of caffeine following prolonged mental exertion is therefore likely to assist in relieving some of the symptoms of mental fatigue. However, we further propose that the effect of adenosine on impaired endurance performance with mental fatigue is due in part to its interaction with dopamine, and therefore caffeine may not fully reverse the effects of mental fatigue. At this point it must also be noted that although this review focusses its attention on adenosine, it may not be adenosine per se, rather diminishing ATP concentration to perform roles related to neurotransmission, which impair endurance performance when mentally fatigued.

Adenosine Inhibits Dopamine Release

Activation of adenosine receptors has been linked to inhibition of neuronal firing (Fredholm, Johansson et al. 1993), inhibition of neurotransmitter release (Fredholm and Dunwiddie 1988) and decreasing locomotor activity (Durcan and Morgan 1989). Adenosine inhibits the release of most brain excitatory neurotransmitters (Harms, Wardeh et al. 1978, Okada, Kiryu et al. 1997, Fredholm, Battig et al. 1999), especially dopamine (Myers and Pugsley 1986), which is believed to be due to an antagonistic interaction between subtypes of adenosine and dopamine receptors (Ferré, Fuxe et al. 1992). Adenosine receptors are found to be concentrated in the dopamine-rich regions of the brain (Lorist and Tops 2003) and adenosine is believed to modify the affinity of dopamine binding to receptors (Ferré, Fuxe et al. 1992). Injection of an adenosine agonist into the nucleus accumbens of rats produces effects similar to those observed with dopamine depletion or antagonism (Font, Mingote et al. 2008). Dopamine antagonism causes rats to reallocate their behavior away from food-reinforced tasks that have high work requirements, towards less effortful types of food seeking (Salamone, Steinpreis et al. 1991). It is plausible that the antagonistic effect of adenosine on dopamine would have a similar effect on humans during exercise. Mentally fatigued participants have reported increased resistance against further effort (Meijman 2000), as well as recorded lower work outputs during a physical task, compared to a control condition (Brownsberger, Edwards et al. 2013, MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014). This review proposes that increased levels of cerebral adenosine effect endurance performance in two ways, firstly by increasing RPE, and secondly by reducing motivation via an antagonism of dopamine by adenosine.

6.6 Dopamine

Dopamine is a neurotransmitter that is implicated in arousal, reward, learning, the control of motor behavior and motivation (Nestler, Hyman et al. 2001). In animals, dopamine levels in the brain are elevated during exercise, but are reduced at the point of exhaustion (Davis and Bailey 1997). Dopamine receptor functioning has also been found to be related to effects concerning energy expenditure (Szechtman, Talangbayan et al. 1994) and the release of dopamine in the nucleus accumbens has been proposed to be an important part of the neural process that enables organisms to overcome work-related response costs (Salamone, Aberman et al. 1999). Among other functions, the nucleus accumbens is hypothesized to indirectly perform cost/benefit analyses, setting constraints on energy expenditure that influence the relative allocation of responses toward various alternatives, such that accumbens dopamine depletion biases behavior towards lower effort alternatives (Salamone, Aberman et al. 1999). Manipulations of dopamine or indirect manipulations of dopamine agonists and antagonists have been used in an attempt to improve performance on both cognitive and physical tasks. Intracranial stimulation of the ventral tegmental area, an origin of dopamine projections within the central nervous system, motivates rats to run without the need for aversive electric shocks (Burgess, Davis et al. 1991). Administration of a dopamine agonist in humans, increased the descriptor ratings of interesting, exciting and motivating for a mathematical task versus a control trial (Volkow, Wang et al. 2004) and increased the choice of a high-effort high-reward food task in rats (Bardgett, Depenbrock et al. 2009). In contrast, the depletion of dopamine in the nucleus accumbens reduced the choice of a high-effort high-reward task option in rats (Cousins, Atherton et al. 1996). Dopamine reuptake inhibitors have also enabled human participants to maintain a greater power output during cycling time trial in the heat, but not in temperate conditions (Roelands, Hasegawa et al. 2008). The increased dopamine concentrations after dopamine reuptake inhibition has been suggested to counteract the hyperthermia-induced decrease in motivation (Del Arco and Mora 2009), consequently allowing participants to 'push harder' and improve exercise performance. This ability to 'push harder' could be seen as, or related to, the psychological construct of motivation.

Mental Fatigue Reduces Motivation

Although a central component of mental fatigue is described as an 'increased resistance to further effort' and a 'decrease in the level of commitment to the task at hand' (Meijman 2000), few studies within the mental fatigue and physical performance literature have reported a reduction in self-reported motivation. Motivated behaviors however, can be characterized by vigor, persistence and high levels of work output (Salamone and Correa 2009) and reductions in these behaviors are commonly reported with mental fatigue. Change in mood and in particular measures of vigor and subjective fatigue are decreased and increased respectively following prolonged mental exertion (Pageaux, Marcora et al. 2013). Participants disengage earlier from a task when they are mentally fatigued (Marcora, Staiano et al. 2009, Pageaux, Marcora et al. 2013) and power output or speed during a time trial is slower (MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014). Response rate during a cognitive task slows with mental fatigue (Boksem, Meijman et al. 2005) and participants report a reduced willingness to exert effort (van der Linden, Frese et al. 2003). It has been suggested that mental fatigue could, at least partly, result from a loss of motivation to engage in self-initiated tasks and that fatigue would be the consequence of an alteration of the motivational brain circuits (Chaudhuri and Behan 2000). Offering a financial incentive to participants following a bout of mental exertion also improved handgrip time to exhaustion compared to no incentive (Brown and Bray 2016). Mental fatigue has also been viewed as an effort/reward imbalance, and when the effort is proportionally larger than the associated reward, the motivation to engage in the task decreases and mental fatigue appears (Tops, Lorist et al. 2004). We propose that with prolonged mental exertion, cerebral concentration of adenosine is increased, via an increase in brain activation, as well as a reduction in fuel availability. The increased adenosine impacts subsequent endurance performance in two ways, increasing RPE during subsequent effortful tasks, as well as reducing motivation through its interaction with dopamine.

6.7 Psychobiological Model

Finally, the Psychobiological Model of endurance performance (Marcora 2008) has been used by authors to explain impaired endurance performance in a state of mental fatigue (Pageaux, Marcora et al. 2013, MacMahon, Schücker et al. 2014, Smith, Marcora et al. 2014). The model, based on Motivational Intensity Theory (Wright 1996), proposes that performance throughout an exercise task is determined primarily based on perceived exertion and potential motivation. In this context, RPE is a method of quantifying how hard, heavy and strenuous a physical task feels to a participant (Marcora 2010), whilst potential motivation is the highest effort a person is willing to exert in order to succeed in a task (Brehm and Self 1989). In terms of exercise performance, when the effort required by an endurance task is perceived to exceed potential motivation, or when perception of effort is so extreme that continuing the task seems impossible, the person consciously decides to stop exercising. According to this effort-based decision-making model, any factor that influences RPE and/or potential motivation influences endurance performance, even when the physiological capacity to perform endurance exercise is unchanged. It is evident that mental fatigue impairs endurance performance, as evidenced by reduced time to exhaustion (Pageaux, Marcora et al. 2013) and impaired time trial performance (Pageaux, Lepers et al. 2014). It is also clear that mental fatigue increases RPE (Marcora, Staiano et al. 2009, MacMahon, Schücker et al. 2014). Although motivation is reported to be unchanged between trials of mental exertion and a less demanding control task, the subsequent physical performance of participants suggests otherwise. Given the nature of an experimental study, participants will not report that they are any less motivated to complete the given task, in fear of disappointing the researcher or being rejected from the study. We suggest that to a degree, a reduction in motivation is masked behind an increase in RPE, and that the methods used to date to quantify motivation are insufficient.

6.8 Future Directions

In this review, we have proposed that mental fatigue impairs endurance performance via an increase in perception of effort and a concurrent reduction in motivation to expend effort. We propose these effects are mediated by an increase in adenosine accumulation, which is brought about by the greater neuronal activity and greater consumption of glucose and glycogen caused by a demanding cognitive task. Going forward, the hypotheses proposed in this review require experimental investigation to determine their truthfulness. Pharmacological manipulation may serve as one method by which to do this. Substances that inhibit or promote adenosine, as well as inhibit or promote dopamine may be used during exercise performance in humans to compare with changes observed with mental fatigue. Manipulations of diet and feeding prior to or post mental exertion may also be used to determine the role of cerebral fuel on the negative effects of mental fatigue on endurance performance.

There are many scenarios that we believe could fit within this model of fatigue. For instance, the use of transcranial direct current stimulation (tDCS) with the anodal electrode placed over the left motor cortex and cathodal electrode above the shoulder recently improved TTE during an isometric leg extension compared to a control or placebo (Angius, Pageaux et al. 2016). The improvement in time to exhaustion was paralleled with a reduction in RPE. It was suggested that stimulation of the motor cortex reduced the required drive to the muscle, thus reducing the activity of premotor areas and participants perceiving less effort for the same force produced (Angius, Pageaux et al. 2016). Suppression of the motor cortex by repetitive transcranial magnetic stimulation has also shown to increase sense of effort during a force matched task (Takarada, Mima et al. 2014). Along with evidence from other studies (McCloskey, Ebeling et al. 1974, Takarada, Nozaki et al. 2006), it was suggested that the neural mechanisms which increase neuronal input to the motor cortex are likely to be involved in inducing an increase in RPE. Using the current model, it is plausible to suggest that the inhibitory effect of adenosine creates a scenario in which a greater stimulatory input on the affected pathways is required in order to produce a motor output. This stimulatory signal presumably comes from motivational and related centres. We believe that it could be the increased activity in these stimulatory pathways that, as may occur with mental exertion, translates as an increase in RPE. Potential mechanisms to counter the negative effects of mental fatigue on RPE and endurance performance must therefore be examined using this model. Further, with developing technology continued efforts will likely enable us to better summate the stimulatory and inhibitory inputs occurring within the brain during exercise.

This model may also be used to explain the integration of afferent feedback in the generation of RPE. Perception of effort is hypothesised to be related to the activity within various regions of the motor cortex, including the premotor and primary motor areas (de Morree, Klein et al. 2012). Specifically, the corollary discharge theory postulates that an efference copy of the central motor command is sent directly from motor to sensory areas of the brain in order to assist in the generation of perceptions associated with motor output (Christensen, Lundbye-Jensen et al. 2007, Poulet and Hedwig 2007). With increasing exercise intensity, a greater number of motor units are recruited and firing frequency increases, as does the number of efferent copies received by sensory regions within the brain (Duncan, Al-Nakeeb et al. 2006, de Morree, Klein et al. 2012). It is further suggested that corollary discharges do not only generate specific sensation, but also modify the processing of incoming sensory information (Fontes, Okano et al. 2015). Inhibition of motor neurons at a spinal or supraspinal level induced by afferent feedback can potentially be compensated for by an increase in central motor command to ensure the same submaximal force production (Pageaux 2016). This inhibition-induced increase in central motor command results in an increase in RPE. The increase in central motor command would also likely alter the use of cerebral fuel, consequently altering adenosine concentration. Only a few studies have successfully investigated the role of afferent feedback in the generation of RPE, further research must be conducted to determine whether afferent feedback could act in this way.

Finally, greater emphasis must be placed on why mental fatigue may not influence all individuals equally. Like any stressor, we believe that a number of variables will affect the impact that mental exertion has on a participant. Both genetic and environmental differences are likely to contribute to baseline cerebral fuel stores, the efficiency of neural processing, development of different regions of the brain and personality traits and attributes. As research in the mental fatigue and physical performance literature broadens, a greater focus on the individual responses to prolonged mental exertion must be monitored. Furthermore, these genetic and environmental factors should be further examined in order to determine their ability for adaptation, and thus potential to improve tolerance to mental fatigue.

6.9 Summary

The findings presented in the current review provide a physiological rationale for the impairment of endurance performance undertaken in a state of mental fatigue. We hypothesize that prolonged and demanding mental fatigue consumes cerebral glucose and glycogen to a greater extent than a less demanding task or at rest. Adenosine is accumulated due to the greater neuronal activity required by the demanding cognitive task, as well as through a reduction in fuel availability. Adenosine then impairs subsequent endurance performance in two ways, increasing RPE and impairing motivation to expend effort. While this review forms a hypothesis, which still needs to be experimentally tested, it is the first to propose a mechanism for the impaired endurance performance observed with mental fatigue. As it is not until we understand how mental fatigue impairs endurance performance, that we can best find ways to combat it.

Chapter Seven: Discussion of Thesis

Discussion of Thesis

7.1 Summary of Major Findings

The impact of mental fatigue on attention and cognitive performance is well-documented; however, the impact of mental fatigue on physical performance is not. The overarching aim of this thesis was to investigate the effect of mental fatigue on physical performance. Within this aim, three specific research areas were identified: (a) the effect of mental fatigue on maximal intensity and short duration exercise tasks; (b) the impact of mental fatigue on individuals of different performance level and who lead different lifestyles; and (c) the potential mechanism(s) behind the increase in RPE and impairment of endurance performance with mental fatigue. In order to examine these areas, a state of mental fatigue was experimentally induced by the prolonged performance of a demanding cognitive task. Subsequent physical performance was then compared between mental exertion and control conditions. In this thesis we defined mental fatigue as a change in psychobiological state, caused by prolonged periods of demanding cognitive activity. A state of mental fatigue was to be accompanied by changes in subjective ratings of fatigue and changes in mood. In situations where such changes were unable to be determined, the term mental exertion was used to describe the completion of a demanding cognitive task.

No effect of mental fatigue was observed in the performance of a task of maximal strength, explosive power or anaerobic capacity (Chapter Three). The lack of impact of mental fatigue on this type of performance contrasted the impaired time to exhaustion and time trial performance reported previously (Marcora, Staiano et al. 2009, MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014). It was concluded that peripheral mechanisms, rather than perception of effort primarily regulate this type of maximal intensity and short duration exercise performance; therefore, mental fatigue would have limited opportunity to affect this type of performance.

The impact of mental fatigue on cognitive and physical performance between professional and recreational athletes was then compared (Chapter Four). This was the first study to examine the effect of mental fatigue on elite athletes, as well as the first study to directly compare cognitive performance between professional and recreational athletes. During 30 min of an incongruent Stroop task, the professional road cyclists completed significantly more trials correctly than the recreational cyclists, with no difference in accuracy between the levels of cyclist. Despite the higher workload, the professional cyclists did not rate the task as any more mentally demanding than the recreational cyclists. Immediately following the mental exertion and the control task, a 20 min cycling time trial was performed. Consistent with previous research (MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014) the recreational cyclists recorded a lower mean power output and a slower average speed during the mental exertion condition. Time trial performance of the professional cyclists was not different between mental exertion and control conditions. The superior performance of the Stroop task was suggested to be indicative of better inhibitory control in the professional cyclists compared to the recreational ones. These findings may suggest that inhibitory control, or self-regulation, is an important characteristic of successful endurance athletes. Inhibitory control has been suggested to be a trait that is largely stale and genetic (Mischel, Shoda et al. 1989, Friedman, Miyake et al. 2008), but also that it can be improved with training (Muraven, Baumeister et al. 1999, Oaten and Cheng 2004a). Further, mental exertion did not impact either RPE or time trial performance in the professional cyclists, indicating greater resistance to mental exertion.

Extending the results of the previous chapter, we sought to determine the effect of individual lifestyle factors on inhibitory control, and endurance performance in a state of mental fatigue (Chapter Five). In particular we focused on the self-regulatory behaviours of physical training load, occupational cognitive load and occupational emotional load, as well as the physiological variable cardiorespiratory fitness. Occupational cognitive load and physical training load were positively correlated with reaction time during the cognitive task of inhibitory control. A positive effect of exercise on brain health and cognition has been reported previously (Smiley-Oyen, Lowry et al. 2008, Smith, Blumenthal et al. 2010). The better inhibitory control observed with increased levels of occupational cognitive load was novel, although does support the transfer effect of practise of one type of self-regulation to the performance of another (Oaten and Cheng 2004a, Oaten and Cheng 2006, Oaten and Cheng 2007). Occupational cognitive load, physical training load and cardiorespiratory fitness predicted the change in time to exhaustion between mental fatigue and control conditions. A greater occupational cognitive load and greater physical training load was associated with less of a decrement in endurance performance when mentally fatigued. In contrast, a higher level of cardiorespiratory fitness was associated with worse endurance performance when mentally fatigued. Previously, the addition of a cognitive task performed concurrently with a 12 week cycling training program improved cycling time to exhaustion to a greater extent than the cycling program alone (Marcora, Staiano et al. 2015). It is therefore possible that by taxing one's self-regulatory capacity to a greater extent with both high levels of cognitive and physical load, greater subsequent improvements in self-regulation may occur. Given that physical training load was positively correlated with resistance to mental exertion, whereas cardiorespiratory fitness was negatively correlated with resistance to mental exertion may suggest that the act of being physically active may contribute more to self-regulation and mental fatigue resistance than the associated physiological adaptations and improvement in maximal oxygen consumption that are likely to occur due to training.

Finally, combining the results of the previous studies (as well as the findings from studies completed by others concurrently) a physiological mechanism was proposed for the increase in RPE and impaired endurance performance with mental fatigue. It was proposed that cerebral stores of glucose and glycogen are reduced with the increase in brain activation during prolonged and demanding mental exertion. Cerebral adenosine accumulates with increased brain activation and reduced fuel availability, which in turn contributes to an increase in RPE, as well as the modulation of motivation via the interaction between adenosine and dopamine. The combined impact of increased RPE and reduced motivation with mental fatigue then impairs subsequent endurance performance. We further proposed that professional athletes may have increased brain glycogen stores, due to increased physical training and the practise of self-regulatory behaviour. An increase in cerebral fuel stores may minimise the accumulation of adenosine, thereby causing less of an increase in RPE and having less of an impact on motivation, and endurance performance.

A schematic of the major findings summarised above can be found in Figure 7.1.

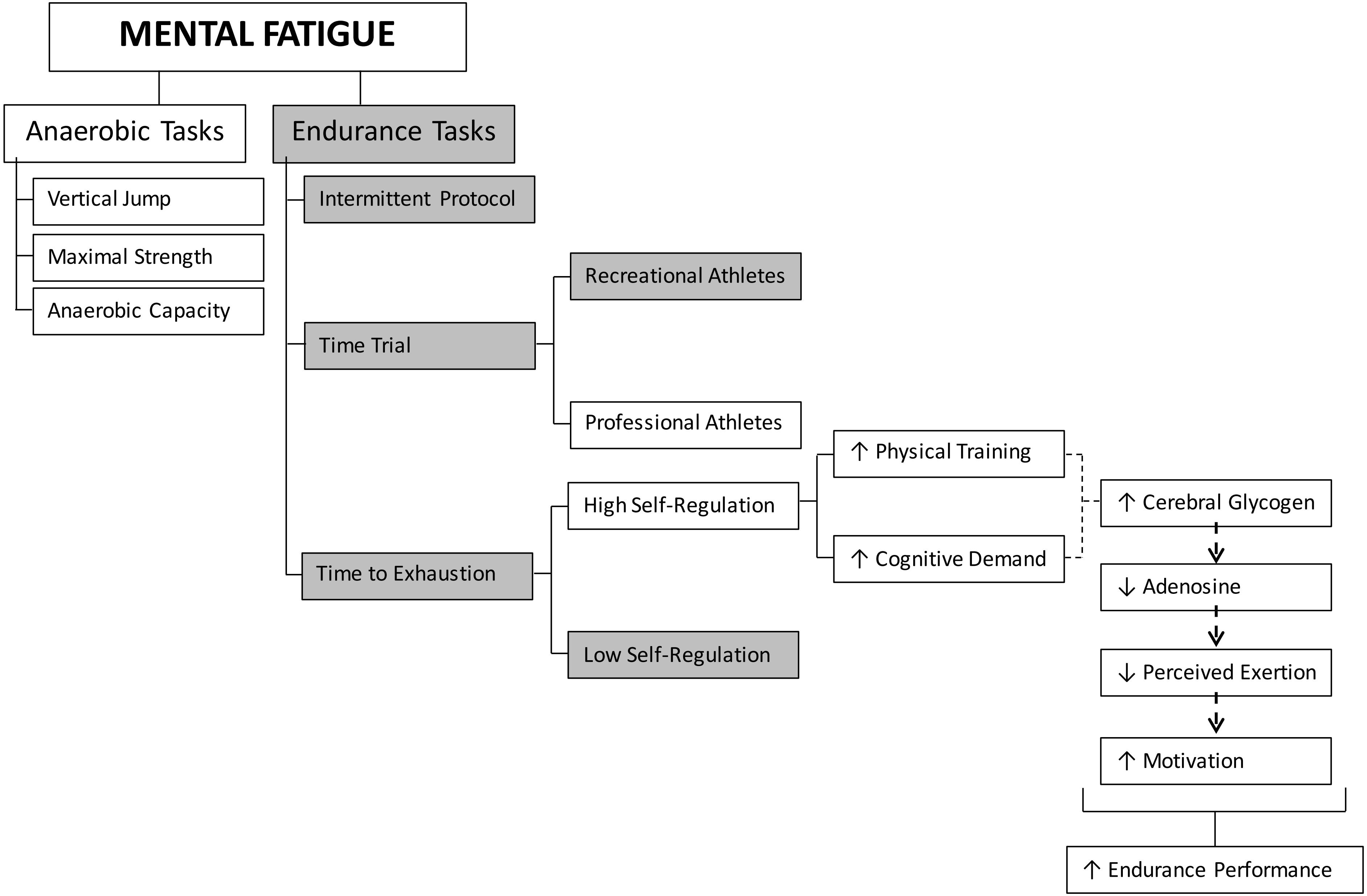
MENTAL FATIGUE
Anaerobic Tasks
Endurance Tasks
Vertical Jump
Maximal Strength
Anaerobic Capacity
Intermittent Protocol
Recreational Athletes
Time Trial
Professional Athletes
↑ Physical Training
High Self-Regulation
↑ Cerebral Glycogen
↑ Cognitive Demand
Time to Exhaustion
↓ Adenosine
Low Self-Regulation
↓ Perceived Exertion
↑ Motivation
↑ Endurance Performance

Figure 7.1 Schematic of the major findings from the thesis. Boxes shaded grey indicates worse performance with mental fatigue. White boxes indicate no effect of mental fatigue on performance. Solid lines indicate evidence is supported by research. Dashed lines indicate current hypotheses

7.2 Comparison with Previous Research

The current thesis was composed of three major research questions. The first was to determine the effect of mental fatigue on short duration and maximal intensity exercise tasks. At the time of undertaking this study, mental fatigue and physical performance literature had only assessed the effect of mental fatigue on endurance style performance tasks. Whilst at the time, our findings of no effect of mental fatigue on maximal leg strength, explosive power or anaerobic capacity contrasted the impaired time to exhaustion (Marcora, Staiano et al. 2009) and time trial performance (MacMahon, Schücker et al. 2014, Pageaux, Lepers et al. 2014) reported previously, these findings have now been supported by further research (Pageaux, Marcora et al. 2013, Rozand, Pageaux et al. 2014, Duncan, Fowler et al. 2015, Pageaux, Marcora et al. 2015). At present there is no valid explanation for the difference in the impact of mental fatigue on endurance and high-intensity exercise tasks. Previous studies have suggested that different types of exercise tasks may recruit different areas of the brain, as well as different brain regions to those involved in the performance of a cognitive task (Rozand, Pageaux et al. 2014). It has also been suggested that different types of exertion (i.e. mental exertion vs. endurance performance) may elicit different neurochemical changes within the brain, which would subsequently have differing effects on performance (Pageaux, Marcora et al. 2013). The author of this thesis contends however, that mental fatigue impacts upon the psychological or perceptual constructs of perceived exertion and motivation, and that endurance exercise tasks are more susceptible to being impacted by these variables than more anaerobic like tasks. In that sense, tasks of longer duration, thereby requiring high levels of motivation sustained over a longer period of time, are likely to be more impacted by mental fatigue than exercise tasks of short duration. Although a short duration, maximal intensity exercise task (i.e.

a countermovement jump) will require motivation to complete the task, motivation does not have to be sustained over a prolonged period of time, and therefore the variables motivation and perceived exertion are less able to impact performance. This proposal could be experimentally tested with manipulations of motivation during endurance performance with mental fatigue, or the repeated performance of anaerobic exercise tasks.

The second area of research, which in the author's opinion contributes most to the current literature, is the finding that there are intra-individual differences in the impact of mental fatigue on endurance performance. Perceived exertion and time trial performance of professional road cyclists was unimpaired following 30 min of metal exertion, compared to the reduced power output and produced by recreational cyclists following mental exertion (Chapter Four). Individuals who participated in greater amounts of occupational cognitive load and physical training load were also better able to maintain endurance performance when mentally fatigued (Chapter Five). Although understandable in early investigations into a research topic, a limitation of previous research was the analysis of the impact of mental fatigue on physical performance as a group, and the subsequent lack of discussion surrounding those individuals whose endurance performance was not affected by mental fatigue. These studies highlight the necessity for researchers in this field to describe participant characteristics beyond anthropometric and physiological capabilities, as these may explain some level of discrepancy between studies. Furthermore, these findings suggest that the ability to tolerate or resist mental exertion may be in some way modifiable, opening up opportunity for exciting new avenues of research.

Another way in which this thesis has contributed to the current pool of research involving mental fatigue and physical performance was to propose a physiological explanation for the increase in RPE and therefore worse endurance performance with mental fatigue. While the wealth of knowledge surrounding the effect of mental fatigue on physical performance is growing, no study has specifically examined, or proposed, the cause or mechanism for the effect. The Psychobiological

Model of Exercise Tolerance (Marcora 2008) has been used to explain the effect of mental fatigue on physical performance. This model can be used to explain why endurance performance is worse following mental exertion, however, it does not explain how mental fatigue actually increases perception of effort, nor why we would see differences in the impact of mental fatigue on endurance performance between professional and recreational athletes, as well as those who participate in high levels of self-regulatory activity and lower levels of self-regulatory activity. Exploring the mechanism behind the effect of mental fatigue on RPE and endurance performance is important to truly understand why the effect occurs and to most effectively design intervention strategies or treatments to reduce the impact of mental fatigue on physical performance.

7.3 Limitations

There are a number of limitations in mental fatigue and physical performance research which must be noted both in the studies contained within this thesis, as well as the other literature cited. Firstly, when comparing between research studies the type and duration of the task used to induce mental fatigue, as well as the conditions the task is performed under vary between the different studies. Although all of the tasks used to induce mental fatigue contain similar components (prolonged duration, sustained attention, response inhibition, and require a fast and accurate response), it is plausible that their reliance on slightly different domains may cause dissimilar effects on the brain, and therefore also on subsequent physical performance. Having said that, two of the more common tasks used to induce mental fatigue, the Stroop colour word task (Hanslmayr, Pastötter et al. 2008) and the AX-CPT (Barch, Braver et al. 1997, Carter, Braver et al. 1998), have been shown to activate the same region of the brain (the ACC – cf. Pardo, Pardo et al. 1990, Larrue, Celsis et al. 1994, Carter, Braver et al. 1998). The mental exertion task, as well as the conditions under which it is performed are therefore important factors to consider when designing a study.

A further limitation of the current literature is the distinction between mental exertion and mental fatigue. Mental exertion is the effort expended to complete a cognitive task. Mental fatigue is the resulting psychobiological state caused by the prolonged mental exertion. In many studies mental fatigue is quantified using psychological or perceptual measures of mental exertion. For example, the NASA-TLX scale asks participants to rate how mentally, temporally and physically demanding a task is, as well as how hard they had to work to accomplish the task. Physiological measures such as heart rate or peripheral blood glucose also attempt to measure changes in the effort expended, rather than the degree of the resulting mental fatigue. It is likely that the lack of a clear definition of mental fatigue is adding to this confusion, however, collectively the way in which mental fatigue is described and quantified needs to be updated. The authors suggest that mental fatigue may be better gauged by the changes in the performance of a subsequent task, rather than the effort an individual expends to actually complete the mentally fatiguing task. This slightly different view to quantifying mental fatigue may also account for the differences we observe in the impact of mental fatigue on physical performance between different individuals, considering those who may be more tolerant to mental exertion than others. Updated methods of assessing mental fatigue would also allow for stronger comparisons of the impact of mental fatigue between individuals and scenarios. The author acknowledges that within chapters contained in this thesis these shortcomings are present. However, in retrospect these are limitations that need to be addressed so future research can move forward most effectively.

Another variable which may cause inconsistency and differences in the results between studies is the use of external motivation to increase engagement with a prolonged and demanding cognitive task designed to induce mental fatigue. Motivation can be manipulated, knowingly or unknowingly, in a number of ways (Jenkins Jr, Mitra et al. 1998, Corbett, Barwood et al. 2012, Winchester, Turer et al. 2012). Within the mental fatigue and physical performance literature, it is common that participants are paid for their time, or offered a monetary reward as an incentive to perform well. Although the finding of worse endurance performance when mentally fatigued is reasonably consistent, higher RPE and a change in motivation is less commonly reported, although this may be due to the methods used to quantify these parameters. To be able to accurately assess the effect of mental fatigue on motivation, any variable which may affect pre-task motivation, or could be an external form of motivation, needs to be controlled. Chapters Four and Five attempt to do this by not rewarding subjects for their participation in the study, nor were participants aware of their own performance or the performance of others. The same researcher was present at all trials, and an effort was made to use the same language and timing of the encouragement between trials. During the physical performance tasks, physiological variables such as heart rate, and performance data such as distance completed were hidden from participants. Participants were also unaware of the true study aims and hypotheses. It must also be considered that the type of person who volunteers to complete an unpaid or unrewarded study of mental fatigue may have their own external motivation. Although attempting to control for manipulations of motivation is a step in the right direction, further research is needed to truly understand the effect of mental fatigue on motivation, how this change affects physical performance and psychological variables, and how we can utilise this information to enhance performance when mentally fatigued. Until this information becomes available, motivation must be noted as a potential confounding variable in any kind of physical performance study.

A final and obvious limitation of the current research is the lack of brain level measurements. We have speculated, using evidence gained from studies in other modes of fatigue (i.e. sleep deprivation), as well as in vitro and animal studies, that cerebral fuel stores, adenosine and modulation of dopamine may play an important role in the effect of mental fatigue on physical performance. This speculation however remains hypothetical until we can investigate changes in fuel and concentrations of neurotransmitters in the brains of mentally fatigued humans. With studies of mental fatigue, replica experiments in animals do not quite do justice. Researchers cannot ask a mouse to complete a cognitive task, record an RPE or perform a time trial. If we could manipulate fuel stores in the brain, as well as that of adenosine and dopamine we may be able to indirectly assess this hypothesis, however, as with any study of the brain in humans, safety is always a major concern. With improvements in imaging technology and the measurement of brain activity the authors are optimistic that more direct studies may be able to be completed soon.

Although the breadth of research investigating the impact of mental fatigue on physical performance is rapidly expanding, much of this research is conducted, or jointly conducted, by researchers in the same group. This in itself is not necessarily a limitation, however, it could be said that a one-sided view of the results occurs because of this fact. One example of a one-sided view is the near exclusivity of the psychobiological model to explain the negative impact of mental fatigue on endurance performance. At present the psychobiological model certainly comes closest to being able to explain the impaired endurance performance observed with mental fatigue, bringing together physiological and psychological variables to explain performance. However, there are still aspects of the impact of mental fatigue on physical performance that the model is unable to explain, such as the lack of impact of mental fatigue on anaerobic type exercise tasks and professional cyclists. As discussed in Chapter 2, the Strength Model of Self-Control has also been used by authors to explain the worse endurance performance of individuals following prolonged mental exertion. This model may argue that a greater degree of 'self-control' is required to undertake a prolonged endurance task compared to a shorter anaerobic task in a state of mental fatigue, and that any task which requires self-control will impair subsequent tasks requiring self-control. However, this model is still unable to explain the superior performance of the professional cyclists. While this thesis and majority of mental fatigue and physical performance research to date have discussed research findings in relation to the psychobiological model, a more broadened approach may elucidate some of the remaining questions. In future, looking at other areas of research may assist sport and exercise science researchers to answer some of their unanswered questions.

7.4 Practical Applications

Several of the findings that have arisen from this thesis may have practical applications in a real-world scenario. It is unlikely that anyone would complete an incongruent Stroop task or the like, voluntarily, or for prolonged periods throughout the day, however, mental fatigue arising from an occupational setting is likely to be common. Understanding the effects of mental fatigue on both physical performance and perceptual variables are therefore important. In a nation struggling with the consequences of physical inactivity and obesity, acknowledgement of the impact that mental fatigue has on endurance performance and RPE is likely of interest to individuals who partake in endurance type exercise following a day at work, or who are trying to fit in physical training sessions around full-time work or study commitments. Considering the consistent reporting of detrimental effects of mental fatigue on endurance performance, but no impact on shorter-duration and higher intensity exercise (i.e. resistance training, anaerobic exercise), physical training schedules may be reorganised to include endurance exercise first thing in the morning, whilst resistance training or anaerobic exercise are completed later in the day. Even for those who are unable to alter their schedules simply the understanding that mental fatigue may increase perception of effort but does not have any effect on any form of peripheral physiological variable may encourage individuals to pursue their physical activity despite it feeling 'hard'.

Assessing individuals on a cognitive task of inhibitory control may also be used as an additional tool in measures of talent identification in endurance athletes. Professional cyclists performed better on a cognitive task of inhibitory control, compared to competitive recreational cyclists, and this was suggested to be reflective of a greater capacity for self-regulation. Although research such as this needs to be supported by larger scale studies, as well as studies involving a range of professional endurance athletes, it is plausible that superior inhibitory control is a psychobiological characteristic of successful endurance athletes. At an anecdotal level, this association is plausible because an endurance athlete with better inhibitory control is more likely to persist with strenuous training programs, dietary restrictions, and limitations to his/her social life while also being better able to exert control over his/her thoughts, feelings and actions during competitions.

Potentially, the finding with the greatest practical application is that tolerance to mental exertion may be modifiable by the practise of lifestyle behaviours requiring self-regulation. Chapter Five demonstrated that individuals who had a greater occupational cognitive load and who completed a greater amount of physical training tended to perform better on a task of inhibitory control, as well as were better able to maintain endurance performance when mentally fatigued. Many occupations require sustained cognitive effort coupled with physical exertion. For example, long haul train drivers, truck drivers or pilots must maintain concentration for prolonged periods of time, as well as be ready to react to any incident that may occur. Although driving or piloting may not seem a very physical task, slowed reaction time or the poor performance of a skilled manoeuvre could risk the safety of many. Similarly, paramedics, firemen, soldiers and surgeons often work long hours, with a significant skill or physical component. Many of these occupations also involve shift work and therefore, sleep deprivation may also amplify the effects of mental fatigue. To this end, highlighting the potential benefit of regular physical activity to individuals concerned about performance decrements associated with mental fatigue is important. In addition, the practise of a task of self-regulation, especially one involving cognitive and/or physical exertion, may also be beneficial as an additional intervention in the treatment of other deficiencies in self-regulation such as alcoholism, obesity and gambling. If improvements in self-regulatory capacity mediate the greater tolerance to mental fatigue of those who undertake both cognitively and physically demanding activities regularly, these benefits may extend beyond mental fatigue to other situations requiring self-regulation.

7.5 Future Research

There are three particular avenues of interest that the author believes future research should focus on. The first would be a direct extension of the findings of Chapter Five. In this study a greater occupational cognitive load and greater physical training load was associated with better performance on a cognitive task of inhibitory control, as well as better maintenance of endurance performance with mental fatigue. A study designed to assess the effectiveness of conscious increases in the level of cognitive and physical exertion in the life of an individual, in improving tolerance to mental fatigue would allow stronger conclusions to be drawn from these findings. Can increases in these self-regulatory lifestyle behaviours actually improve tolerance to mental fatigue, and further, does a greater stimulus (i.e. increasing the amount of both physical and mental exertion, practising one versus two different types of self-regulation, or 30 min per day versus 60 min per day) produce greater adaptation? Depending on the results, these tasks or interventions may then be tailored to suit different scenarios and/or different occupations. A study of a more longitudinal nature may also allow for investigation into the potential mechanisms behind improvements in performance with the practise of self-regulation.

In keeping with exploring the mechanism behind an effect, future research must focus on the action by which mental fatigue increases RPE and thereby impairs subsequent endurance performance. This may take the form of testing the physiological mechanism proposed in Chapter Six. Indirect manipulations of glycogen, caffeine, adenosine and dopamine would all lend support or opposition to this model. Recently, the effects of caffeine ingestion on physiological and perceptual responses in mentally fatigued participants were examined (Azevedo, Silva-Cavalcante et al. 2016). Ingestion of 5 $mg.kg^{-1}$ of body weight of caffeine improved cycling time to exhaustion following 90 min when participants ingested a placebo, or nothing. A greater amount of work was produced during the caffeine trial, with no significant differences between experimental conditions for any cardiorespiratory, metabolic, or neuromuscular variables. Despite differences in time to exhaustion, RPE was also not different during the final stages of the test different between trials. Maintenance of vigour and a reduction in fatigue with caffeine ingestion was suggested to underlie the improved endurance performance in a state of mental fatigue. These findings support the role of adenosine in the negative effect of mental fatigue on RPE and endurance performance. Variations on this study, including ingestion of glucose and dopamine agonists would further support changes in brain metabolism and neurotransmitters underlying the impact of mental fatigue on performance.

Research investigating methods by which we can reduce the impact of mental fatigue on subsequent cognitive and physical performance is also highly important. These studies may work in a number of ways. Pharmacological and/or nutritional manipulations, such as the aforementioned investigations of glucose, caffeine and dopamine agonists may be used to target the increase in RPE with mental fatigue. With no change in any peripheral physiological variable with mental fatigue, any manipulation which would diminish an increase in RPE would likely improve subsequent physical performance. Various manipulations of motivation may also reduce the negative effect of mental fatigue on endurance performance. Chapter Six proposes that endurance performance may be impaired by mental fatigue via an increase in RPE, as well as a reduction in motivation mediated by increased levels of cerebral adenosine. Experimentally manipulating motivation may help overcome the hypothesised adenosine induced reduction in motivation. Direct competition (Corbett, Barwood et al. 2012), motivational self-talk (Blanchfield, Hardy et al. 2013) and the presence of an attractive research assistant (Winchester, Turer et al. 2012) have all been shown to improve endurance performance compared to when the motivating stimulus was absent. These strategies may provide a novel method for overcoming the detrimental effect of mental fatigue, however, manipulation of motivation may have varying effects on different individuals and the type or form of motivation manipulated is important. For example, external incentives such as money and status have been linked with athlete burnout (Cresswell and Eklund 2005) and dropout (Pelletier, Fortier et al. 2001), and when pressure to perform is increased, individuals commonly perform worse than without such pressure (i.e. 'choking')(Beilock and Carr 2001). Intrinsic motivation is defined as the doing of an activity for its inherent satisfactions rather than for some separable consequence (Ryan and Deci 2000). Intrinsically motivated behaviours are associated with improved longer term outcomes, as they are strongly associated with pleasure, enjoyment and positive subjective experiences, the opposite is true for more extrinsic forms of motivation (Frederick and Ryan 1995, Vansteenkiste and

Lens 2006). As such, situations in which an individual is performing a task because of intrinsic motivation, presenting the individual with extrinsic motivation to perform the activity may undermine intrinsic motivation and thus reduce effort and persistence (Deci, Koestner et al. 1999). These factors need to be considered, as well as rehearsed prior to implementation.

Figure 7.2 summarises potential methods that may be useful in overcoming some of the detrimental effects of mental fatigue on endurance performance.

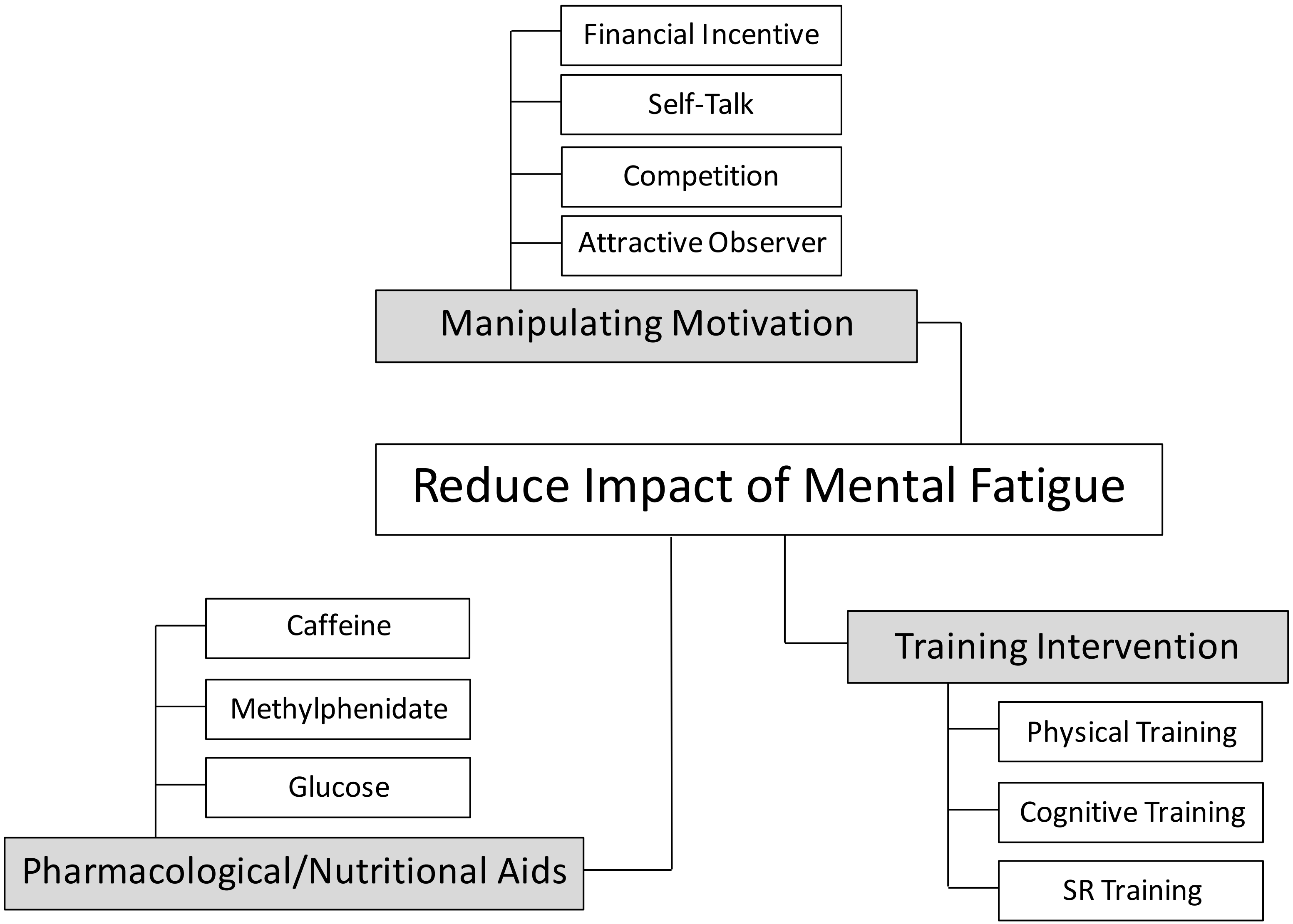
Financial Incentive
Self-Talk
Competition
Attractive Observer
Manipulating Motivation
Reduce Impact of Mental Fatigue
Caffeine
Methylphenidate
Glucose
Pharmacological/Nutritional Aids
Training Intervention
Physical Training
Cognitive Training
SR Training

Figure 7.2 Potential areas of investigation to reduce the negative impact of mental fatigue on rating of perceived exertion and subsequent endurance performance. SR – Self regulation

7.6 Conclusion

The aim of this thesis was to further investigate the effect of mental fatigue on physical performance. We determined that mental fatigue does not impair maximal anaerobic exercise tasks; that professional endurance athletes are more resistant to mental fatigue than recreational athletes; that practise of self-regulatory behaviour is associated with better maintenance of endurance performance with mental fatigue; and we proposed a physiological mechanism for the increase in RPE and worse endurance performance observed with mental fatigue. Our findings support those of early mental fatigue research which suggest that perception of effort, rather than cardiorespiratory and musculoenergetic mechanisms account for worse physical performance with mental fatigue. However, the current thesis extends this work by highlighting differences in the impact of mental fatigue between individuals, as well as proposing a physiological mechanism for mental fatigue that arises within the brain. This research should act as a solid foundation for future research in this area, focussing in particular on ways to improve tolerance to mental fatigue, as well as uncovering the physiological mechanism behind the detrimental effect. Only when we know the way by which mental fatigue impairs physical performance, will prevention or treatment for reducing the impact of mental fatigue be truly possible.

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APPENDICES

Appendix A1 – Ethics Approval (Chapter Three)

UNIVERSITY OF CANBERRA
AUSTRALIA'S CAPITAL UNIVERSITY

7 May 2013

APPROVED - Project number 13-71

Ms Kristy Martin
Faculty of Health
University of Canberra
Canberra ACT 2601

Dear Kristy,

The Human Research Ethics Committee has considered your application to conduct research with human subjects for the project **The effect of mental fatigue on short-term exercise performance.**

Approval is granted until 30 March 2014, the anticipated completion date stated in the application.

The following general conditions apply to your approval.

These requirements are determined by University policy and the ***National Statement on Ethical Conduct in Human Research*** (National Health and Medical Research Council, 2007).

Monitoring:	You, in conjunction with your supervisor, must assist the Committee to monitor the conduct of approved research by completing and promptly returning project review forms, which will be sent to you at the end of your project and, in the case of extended research, at least annually during the approval period.
Discontinuation of research:	You, in conjunction with your supervisor, must inform the Committee, giving reasons, if the research is not conducted or is discontinued before the expected date of completion.
Extension of approval:	If your project will not be complete by the expiry date stated above, you must apply in writing for extension of approval. Application should be made before current approval expires; should specify a new completion date; should include reasons for your request.
Retention and storage of data:	University policy states that all research data must be stored securely, on University premises, for a minimum of five years. You must ensure that all records are transferred to the University when the project is complete.
Contact details and notification of changes:	All email contact should use the UC email address. You should advise the Committee of any change of address during or soon after the approval period including, if appropriate, email address(es).

Please add the Contact Complaints form (attached) for distribution with your project.

Yours sincerely
Human Research Ethics Committee

Hendryk Flaegel
Ethics & Compliance Officer
Research Services Office
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Appendix A1 – Ethics Approval (Chapter Four)

UNIVERSITY OF CANBERRA
AUSTRALIA'S CAPITAL UNIVERSITY

3 March 2014

APPROVED - Project number 14-18

Ms Kristy Martin
Faculty of Health
University of Canberra
Canberra ACT 2601

Dear Kristy,

The Human Research Ethics Committee has considered your application to conduct research with human subjects for the project titled **The Effects of Cognitive Load on Exercise Performance in Recreational and Elite Athletes.**

Approval is granted until 1 March 2016.

The following general conditions apply to your approval.

These requirements are determined by University policy and the ***National Statement on Ethical Conduct in Human Research*** (National Health and Medical Research Council, 2007).

Monitoring:	You, in conjunction with your supervisor, must assist the Committee to monitor the conduct of approved research by completing and promptly returning project review forms, which will be sent to you at the end of your project and, in the case of extended research, at least annually during the approval period.
Discontinuation of research:	You, in conjunction with your supervisor, must inform the Committee, giving reasons, if the research is not conducted or is discontinued before the expected date of completion.
Extension of approval:	If your project will not be complete by the expiry date stated above, you must apply in writing for extension of approval. Application should be made before current approval expires; should specify a new completion date; should include reasons for your request.
Retention and storage of data:	University policy states that all research data must be stored securely, on University premises, for a minimum of five years. You must ensure that all records are transferred to the University when the project is complete.
Contact details and notification of changes:	All email contact should use the UC email address. You should advise the Committee of any change of address during or soon after the approval period including, if appropriate, email address(es).

Yours sincerely
Human Research Ethics Committee

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Appendix A1 – Ethics Approval (Chapter Five)

UNIVERSITY OF CANBERRA
AUSTRALIA'S CAPITAL UNIVERSITY

3 March 2015

APPROVED - Project number 15-26

Ms Kristy Martin
Faculty of Health
University of Canberra
Canberra ACT 2601

Dear Kristy,

The Human Research Ethics Committee has considered your application to conduct research with human subjects for the project titled **Do endurance training adaptations increase resistance to mental fatigue?**

Approval is granted until 1 February 2016.

The following general conditions apply to your approval.

These requirements are determined by University policy and the ***National Statement on Ethical Conduct in Human Research*** (National Health and Medical Research Council, 2007).

Monitoring:	You must, in conjunction with your supervisor, assist the Committee to monitor the conduct of approved research by completing and promptly returning project review forms, which will be sent to you at the end of your project and, in the case of extended research, at least annually during the approval period.
Discontinuation of research:	You must, in conjunction with your supervisor, inform the Committee, giving reasons, if the research is not conducted or is discontinued before the expected date of completion.
Extension of approval:	If your project will not be complete by the expiry date stated above, you must apply in writing for extension of approval. Application should be made before current approval expires; should specify a new completion date; should include reasons for your request.
Retention and storage of data:	University policy states that all research data must be stored securely, on University premises, for a minimum of five years. You must ensure that all records are transferred to the University when the project is complete.
Contact details and notification of changes:	All email contact should use the UC email address. You should advise the Committee of any change of address during or soon after the approval period including, if appropriate, email address(es).

Yours sincerely
Human Research Ethics Committee

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Appendix A2 – Peer Reviewed Publications (Chapter Three)

Eur J Appl Physiol
DOI 10.1007/s00421-014-3052-1

ORIGINAL ARTICLE

Mental fatigue does not affect maximal anaerobic exercise performance

Kristy Martin · Kevin G. Thompson · Richard Keegan · Nick Ball · Ben Rattray

Received: 31 July 2014 / Accepted: 10 November 2014

Abstract

Purpose Mental fatigue can negatively impact on submaximal endurance exercise and has been attributed to changes in perceived exertion rather than changes in physiological variables. The impact of mental fatigue on maximal anaerobic performance is, however, unclear. Therefore, the aim of the present study was to induce a state of mental fatigue to examine the effects on performance, physiological and perceptual variables from subsequent tests of power, strength and anaerobic capacity.

Methods Twelve participants took part in the single-blind, randomised, crossover design study. Mental fatigue was induced by 90 min of the computer-based Continuous Performance Task AX version. Control treatment consisted of 90 min of watching emotionally neutral documentaries. Participants consequently completed countermovement jump, isometric leg extension and a 3-min all-out cycling tests.

Results Results of repeated measures analysis of variance and paired *t* tests revealed no difference in any performance or physiological variable. Rating of perceived exertion tended to be greater when mentally fatigued (mental fatigue $= 19 \pm 1$ vs control $= 18 \pm 1$, $p = 0.096$, $\eta_p^2 = .232$) and intrinsic motivation reduced (mental fatigue $= 11 \pm 4$ vs control $= 13 \pm 6$, $p = 0.063$, $d = 0.597$) in the mental fatigue condition.

Conclusions Near identical responses in performance and physiological parameters between mental fatigue and control conditions suggest that peripheral mechanisms primarily regulate maximal anaerobic exercise. Whereas mental fatigue can negatively impact submaximal endurance exercise, it appears that explosive power, voluntary maximal strength and anaerobic work capacity are unaffected.

Keywords Mental fatigue · Peripheral · Power · Strength · Anaerobic capacity

Abbreviations

3MT	Three-minute all-out cycle test
ANOVA	Analysis of variance
AX-CPT	Continuous performance test AX version
CMJ	Countermovement jump
CON	Control
EMG	Electromyography
MF	Mental fatigue
POMS	Profile of mood states
RPE	Rating of perceived exertion
RSME	Rating scale of mental effort
SIMS	Situational intrinsic motivation scale

Communicated by Jean-René Lacour.

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Introduction

Mental fatigue is a change in psychobiological state, caused by prolonged periods of demanding cognitive activity (Marcora et al. 2009). This change is gradual and cumulative and has subjective and objective manifestations including increased resistance against further effort (Meijman 2000), changes in mood (Holding 1983) and

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Appendix A2 – Peer Reviewed Publications (Chapter Four)

PLOS | ONE

RESEARCH ARTICLE

Superior Inhibitory Control and Resistance to Mental Fatigue in Professional Road Cyclists

Kristy Martin[1☯], Walter Staiano[2☯], Paolo Menaspà[3], Tom Hennessey[1], Samuele Marcora[4*], Richard Keegan[1], Kevin G. Thompson[1], David Martin[5], Shona Halson[5], Ben Rattray[1]

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☯ These authors contributed equally to this work.
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Citation: Martin K, Staiano W, Menaspà P, Hennessey T, Marcora S, Keegan R, et al. (2016) Superior Inhibitory Control and Resistance to Mental Fatigue in Professional Road Cyclists. PLoS ONE 11(7): e0159907. doi:10.1371/journal.pone.0159907

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Funding: These authors have no support or funding to report.

Competing Interests: The authors have declared that no competing interests exist.

Abstract

Purpose

Given the important role of the brain in regulating endurance performance, this comparative study sought to determine whether professional road cyclists have superior inhibitory control and resistance to mental fatigue compared to recreational road cyclists.

Methods

After preliminary testing and familiarization, eleven professional and nine recreational road cyclists visited the lab on two occasions to complete a modified incongruent colour-word Stroop task (a cognitive task requiring inhibitory control) for 30 min (mental exertion condition), or an easy cognitive task for 10 min (control condition) in a randomized, counterbalanced cross-over order. After each cognitive task, participants completed a 20-min time trial on a cycle ergometer. During the time trial, heart rate, blood lactate concentration, and rating of perceived exertion (RPE) were recorded.

Results

The professional cyclists completed more correct responses during the Stroop task than the recreational cyclists (705±68 vs 576±74, $p = 0.001$). During the time trial, the recreational cyclists produced a lower mean power output in the mental exertion condition compared to the control condition (216±33 vs 226±25 W, $p = 0.014$). There was no difference between conditions for the professional cyclists (323±42 vs 326±35 W, $p = 0.502$). Heart rate, blood lactate concentration, and RPE were not significantly different between the mental exertion and control conditions in both groups.

Conclusion

The professional cyclists exhibited superior performance during the Stroop task which is indicative of stronger inhibitory control than the recreational cyclists. The professional

Appendix A3 – Conference Communications (Chapter Three)

Mental fatigue does not effect subsequent short-term exercise performance

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Background

MENTAL FATIGUE is a change in psychophysiological state, caused by prolonged periods of demanding cognitive activity.

Mental fatigue can be brought about by sustained performance of a single cognitive task or combined different tasks that require mental effort, such as fatigue because of a day in the office.

Mental fatigue has ↓ performance of time to exhaustion during high-intensity cycling[1], a prolonged isometric contraction of knee extensors[2] and a 5 km running time trial[3].

Whilst the negative impact of mental fatigue on endurance performance has been established, short-term tasks of power, strength and anaerobic capacity are more ecologically valid and outcome related in both sporting and occupational settings. Therefore the aim of this study was to determine;

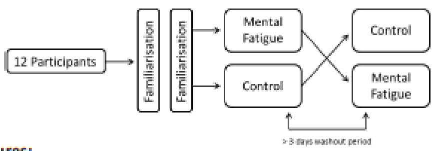
Does mental fatigue affect subsequent short-term exercise performance?

Methods

Session 1: 12 Participants, involved in regular (2 x week) high-intensity exercise, were assessed for maximal oxygen uptake to determine the workload for the 3MT[4].

Session 2 & 3: Familiarisation of the 3MT and recorded measures.

Session 4 & 5: Baseline vertical jump (VJ) and isometric leg extension (EXT), 90 min of a cognitively demanding computer task (AX-CPT) or a control (watching an emotionally neutral documentary), then recompletion of the VJ, EXT and 3MT.



Measures:

- ***Performance:*** Jump height, torque, work completed & pacing of 3MT
- ***Physiological & Perceptual:*** HR, lactate concentration, RPE & motivation
- ***Manipulation Check:*** RT, % correct, mental effort (RSME) & mood

Results

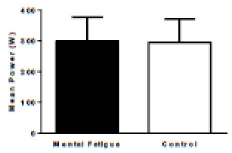


Figure 1. Mean power during 3MT

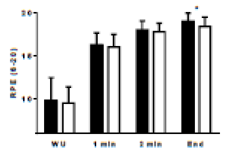


Figure 2. Perceived exertion during 3MT

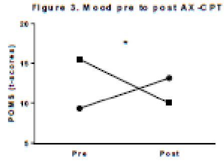


Figure 3. Mood pre to post AX-CPT

Paired t-tests were used to compare RT, RSME, motivation and mood from the beginning to the end of the AX-CPT. Repeated measures ANOVAs were used to test the effect of condition and time on all other measures.

- ***Performance:*** No difference in performance or pacing variables (fig 1).
- ***Physiological & Perceptual:*** End RPE ↑ when fatigued (19±1 vs 18±1, p=0.046, d=0.66). No other perceptual or physiological difference (fig 2).
- ***Manipulation Check:*** RT increased by 20%, RSME was 159% greater, fatigue increased by 44% and vigour decreased by 67% post AX-CPT (fig 3).

Discussion/Conclusion

Consistent with previous research[1-3] mental fatigue ↑ RPE during exercise, however did not extend to a difference between conditions for any performance variable. There are two possible hypotheses;

1. Tests of high-intensity and short duration are significantly influenced by peripheral fatigue, and therefore physiological factors outside of central mediators may primarily determine performance outcomes[5].

2. The Psychobiological Model of Exercise Tolerance[6] postulates that performance is ultimately determined by two cognitive and motivational factors: perceived exertion and potential motivation. Simply participants 'give up' because the effort required for the task exceeds the effort they are willing to exert, or because the effort to complete the task is beyond their perceived ability. In the present study the short and predetermined duration of the 3MT increased potential motivation to match the greater perceived exertion.

This study suggests that short-term exercise performance is not affected by mental fatigue.

References

1. Mental fatigue impairs physical performance in humans (Marcora et al. 2009)
2. Prolonged mental exertion does not alter neuromuscular function of the knee extensors (Pageaux et al. 2013)
3. Response inhibition impairs subsequent self-paced endurance performance (Pageaux et al. 2014)
4. A 3-min all-out test to determine peak oxygen uptake and the maximal steady state (Burnley et al. 2006)
5. Effects of supramaximal exercise on the electromyographic signal (Hunter et al. 2003)
6. Afferent feedback from fatigued locomotor muscles is not an important determinant of endurance exercise performance (Marcora et al. 2010)

CRICOS #00212K

Appendix A3 – Conference Communications (Chapter Four)

MO-BN07 Cognitive impairments and fatique during exercise

MENTAL EXERTION DOES NOT AFFECT ELITE CYCLISTS

Martin, K., Staiano, W., Menaspa, P., Marcora, S., Halson, S., Martin, D.T., Thompson, K.G., Keegan, R., Rattray, B.
University of Canberra

Introduction: Mental fatigue (MF) increases perceived exertion (RPE) and impairs endurance performance in recreationally-trained athletes (Marcora 2009; Pageaux 2014). The effect of MF on elite athletes is unknown. The aim of the study was to assess the performance, physiological and psychological responses of elite cyclists following a bout of mental exertion. Methods: Nine elite road cyclists completed 30 min of an incongruent Stroop colour-word task, previously used to induce MF in recreational runners (Pageaux 2014), or 30 min of a passive control task in a double blind cross-over study. Following each treatment, participants completed a standardised warm-up and a 20 min cycling time trial (TT). Performance, physiological and psychological measures were recorded throughout the Stroop task and TT. Results: The Stroop task was rated as more mentally demanding ($p<0.001$), requiring more effort ($p<0.001$) and eliciting greater subjective ratings of fatigue ($p=0.005$) than the control task. Blood glucose concentration tended to increase throughout the Stroop task ($p=0.053$). During the TT, there was no difference between conditions for mean power ($p=0.983$), total distance covered ($p=0.491$) or pacing profile ($p=0.777$). RPE increased over time ($p<0.001$) but was identical between conditions ($p=1.00$). Discussion: Mental exertion did not affect RPE or TT performance in elite cyclists. These findings contrast those observed in recreational athletes (Pageaux 2014). The negative impact of MF on endurance performance has been attributed to an accumulation of adenosine in the anterior cingulate cortex, the primary sensory input for RPE (Pageaux 2014). Adenosine accumulates under periods of increased energy demand and reduced energy availability. Training-induced increases in basal cerebral glycogen levels have been observed in rats following 4 weeks of endurance training (Matsui 2012). A similar adaptation in the elite cyclists would subsequently minimise adenosine accumulation and disruption to RPE and performance. In support of this hypothesis, blood glucose concentration in this study tended to increase throughout the Stroop task, also in contrast to findings in recreational athletes (Marcora 2009: Pageaux 2014). Elite athletes therefore may possess training-induced adaptations and experience which afford them the ability to reproduce exercise performance following mental exertion. References: Marcora S, Staiano W, Manning V. (2009). J Appl Physiol, 106, 857-64 Pageaux B, Lepers R, Dietz K, Marcora S. (2014). Eur J Appl Physiol, 114, 1-11 Matsui T, Ishikawa T, Ito H, Okamoto M, Inoue K, Lee M, et al. J Physiol. (2012). 590, 607-16 Contact: kristy.martin@canberra.edu.au

Appendix A3 – Conference Communications (Chapter Four and Chapter Six)

227 The brain of an elite athlete: Do physical training adaptations extend to the brain?

AWARD FINALIST

K. Martin[1]* • W. Staiano[2] • P. Menaspa[3] • R. Keegan[1] • T. Hennessey[1] • S. Marcora[2] • S. Halson[3] • D. Martin[3] • K. Thompson[1] • B. Rattray[1]
[1]University of Canberra Research Institute for Sport and Exercise • [2]School of Sport and Exercise Sciences, University of Kent • [3]Australian Institute of Sport

Introduction: Prolonged mental exertion (ME) compromises endurance performance in moderately-trained participants. The impact of ME on elite athletes is unknown. This study sought to determine whether characteristics, specific to elite athletes, affect the impact of ME on physiological, psychological and performance variables.
Methods: Nine elite road cyclists (6 AIS world touring squad members, 3 national level cyclists) and nine recreational level cyclists completed 30 min of an incongruent Stroop colour-word task, previously used to induce mental fatigue in recreational runners, or 30 min of a passive control task in a double-blind cross-over study. Following each treatment, participants completed a standardised warm-up and 20 min cycling time trial (TT). Physiological and psychological measures were recorded throughout the tasks and TT. Two- and three-way repeated measures ANOVAs determined interactions and differences between tasks, level of cyclist and time.
Results: The Stroop task was rated more mentally demanding ($p<0.01$, $\eta^2p=0.88$), requiring more effort ($p<0.01$, $\eta^2p=0.90$) and being more frustrating ($p<0.01$, $\eta^2p=0.89$) than the control task. The elite cyclists saw no difference between tasks for mean power ($p=0.98$, $\eta^2p<0.01$), average speed ($p=0.48$, $\eta^2p=0.07$) or total distance ($p=0.49$, $\eta^2p=0.07$). Relative to control, the recreational cyclists recorded reduced mean power ($p=0.01$, $\eta^2p=0.55$), slower average speed ($p<0.01$, $\eta^2p=0.68$) and less total distance ($p<0.01$, $\eta^2p=0.63$) following the Stroop task. Blood glucose tended to increase in the elite cyclists during the Stroop task (Pre: 4.9 ± 1.0 to Post: 5.6 ± 1.2 mmol.l^{-1} $p=0.06$, $\eta^2p=0.38$). Perception of effort (RPE) was not different between conditions for either level of cyclist.

Appendix A4 – Other Publications

frontiers in Physiology

REVIEW
published: 17 March 2015
doi: 10.3389/fphys.2015.00079

Is it time to turn our attention toward central mechanisms for post-exertional recovery strategies and performance?

Ben Rattray [1,2]*, *Christos Argus* [2], *Kristy Martin* [1,2], *Joseph Northey* [1,2] *and Matthew Driller* [3]

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Key Points

- Central fatigue is accepted as a contributor to overall athletic performance, yet little research directly investigates post-exercise recovery strategies targeting the brain
- Current post-exercise recovery strategies likely impact on the brain through a range of mechanisms, but improvements to these strategies is needed
- Research is required to optimize post-exercise recovery with a focus on the brain

Post-exercise recovery has largely focused on peripheral mechanisms of fatigue, but there is growing acceptance that fatigue is also contributed to through central mechanisms which demands that attention should be paid to optimizing recovery of the brain. In this narrative review we assemble evidence for the role that many currently utilized recovery strategies may have on the brain, as well as potential mechanisms for their action. The review provides discussion of how common nutritional strategies as well as physical modalities and methods to reduce mental fatigue are likely to interact with the brain, and offer an opportunity for subsequent improved performance. We aim to highlight the fact that many recovery strategies have been designed with the periphery in mind, and that refinement of current methods are likely to provide improvements in minimizing brain fatigue. Whilst we offer a number of recommendations, it is evident that there are many opportunities for improving the research, and practical guidelines in this area.

Keywords: recovery, brain, mental fatigue, sleep, nutrition

Introduction

Recovery from exercise is the process whereby the body is returned to a pre-exercise state (Halson and Jeukendrup, 2004; Barnett, 2006). The recovery process is of particular importance to athletes who are required to perform optimally over subsequent training sessions and competitions (Barnett, 2006). Although recovery from exercise occurs naturally over time, there is a desire by athletes and coaches to accelerate this process where time