# MENTAL FATIGUE AND EXERCISE PERFORMANCE

**By**

**Neil Paul Dallaway**

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**The School of Sport, Exercise and Rehabilitation Sciences**

**College of Life and Environmental Sciences**

**University of Birmingham**

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## Abstract

An investigation of cognitive task engagement and subsequent muscular endurance performance and brain endurance training (BET) - increased cognitive demand during physical training. Chapter two utilised a triple task (cognitive–physical–cognitive) to investigate the dose-response of a response inhibition task on submaximal handgrip. Handgrip was impaired following cognitive tasks of 10 minutes but not after 5 and 20 minutes. Learning effects occurred during the 20 minute cognitive task. A prior response inhibition task improved performance in a novel response inhibition task. These results can be explained by cognitive control theory. Chapter three demonstrated that engagement in a mentally demanding cognitive task, without response inhibition, for a period of 20 minutes did not impair submaximal isometric handgrip exercise. Chapter four investigated temporal effect of mental fatigue with 4 blocks of 10 minutes cognitive task followed by 5 minutes of rhythmic handgrip. Over time indices of mental fatigue diverge, with self-report measures accentuating and physiological measures attenuating. After 20 minutes this state of mental fatigue impaired physical performance. Chapter five demonstrated that 6 weeks BET alongside submaximal handgrip training, increased endurance performance by 32%, which occurred with a higher prefrontal cortex oxygenation, relative to 12% improvements in control.

**Conference abstracts from this thesis (to date)**

- Dallaway N, Lucas S.J.E, T, Ring C. (2017, November). Effects of brain endurance training on endurance exercise performance, free communication presentation at the British Association of Sport and Exercise Science annual conference. https://doi.org/10.1080/02640414.2017.1378421
- Dallaway N, Lucas S.J.E, T, Ring C. (2017, June). Effects of brain endurance training on endurance exercise performance, poster presentation at the European Congress of Sports Sciences conference.
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**Awards related to this thesis**

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| | |
|---|---|
| ACC | Anterior cingulate cortex |
| ANCOVA | Analysis of covariance |
| ANOVA | Analysis of variance |
| AX-CPT | AX continuous performance test |
| BET | Brain endurance training |
| CFS | Chronic fatigue syndrome |
| CR | Category ratio |
| HHB | Deoxyhaemoglobin |
| ECG | Electrocardiogram |
| EMG | Electromyography |
| HR | Heart rate |
| HRV | Heart rate variability |
| LSD | Least significant differences |
| M | Mean |
| ME | Mental exertion |
| MF | Mental fatigue |
| MVC | Maximal voluntary contraction |
| NIRS | Near infra-red spectroscopy |

| | |
|---|---|
| O2HB | Oxyhaemoglobin |
| PFC | Prefrontal Cortex |
| POMS | Profile of mood states |
| PVT | Psychomotor vigilance test |
| RMSSD | Root mean square of successive differences of the R-to-R wave interval |
| RPE | Ratings of perceived exertion |
| SD | Standard deviation |
| SDNN | Standard deviation of the R-to-R wave interval |
| SEM | Standard error of the mean |
| SPS | Spatially resolved spectroscopy |
| THI | Total haemoglobin index |
| TT | Time trial |
| TTE | Time to exhaustion |
| TOI | Total oxygenation index |

# 1

# General introduction

## 1.0 Introduction

Chrisse Wellington stated, *"It's when the discomfort strikes that they realise a strong mind is the most powerful weapon of all"*. This quote by the current female ironman distance triathlon world record holder, and four time world champion, epitomises the importance of the ability to tolerate high levels of physical exertion in order to maximise human endurance capacity. The field of sports and exercise science has long examined fatigue as a peripheral physiological concept. The terms of fatigue and exertion have often been used interchangeably, to describe task disengagement from the physical discomfort generated during highly demanding exercise. The role of the brain in the regulation of endurance exercise has become of increased interest in the previous two decades, in the addition to peripheral physiological factors. In the past decade, mental fatigue has extensively been shown to negatively impact endurance exercise performance, highlighting the importance of higher order executive processes in regulating the physiological responses to exercise and the perception of effort. From a sports psychology research perspective, the strength control model has often been used to explain how the concept of a global self-control resource and a depletion of willpower can impair muscular endurance performance. However, gaps remain in the research regarding the role of mental fatigue and self-control in regulating endurance exercise performance, which needs to be addressed. Additionally, there has been a limited amount of research in understanding individual differences to exercise tolerance and training strategies to increase tolerance to high levels of physical exertion. The body of research, presented in this thesis, will attempt to address these gaps and investigate if building resilience to the negative effects of mental fatigue can increase exercise tolerance and ultimately improve exercise performance.

This general introduction will start by defining the different types of fatigue before outlining the competing theories of brain regulation of endurance exercise performance. Specifically, they will be evaluated on how they differ in the neurophysiological generation of the perception of effort. A brief overview of the research on mental fatigue and endurance exercise performance will be given, before finally outlining the specific questions this body of research aims to address.

## 1.1 Fatigue

The term fatigue has many different definitions and interpretations leading them open to challenge and debate. This section will outline the commonly used terminology within exercise physiology, and which will be used throughout this thesis. The dictionary definition of fatigue is "*extreme tiredness resulting from mental or physical exertion or illness*". The term 'fatigue' is often characterised as peripheral, central and mental, as well as being used to describe a general subjective sensation in everyday life. Chronic fatigue syndrome (CFS) is a clinical form of extreme fatigue, which is ever present for periods of over 6 months. CFS is very difficult to diagnosis and treat and its causes are unknown [1]. Research with CFS patients can give insight into the implications of prolonged fatigue, such as a reduction in working memory processing speed over a sustained period [2].

### 1.1.1 Muscular fatigue

Muscle fatigue during exercise is multifaceted, complex and task specific and has traditionally been attributed to peripheral system factors such as glycogen depletion and anaerobiosis in skeletal muscle resulting in an inability to maintain the required force production [3]. Muscle fatigue is defined as "any exercise-induced reduction in the ability of a muscle to generate force or power" and is made up of two components; peripheral and central [4]. Peripheral muscular fatigue is produced by changes at, or distal to, the neuromuscular junction, due to exercise-induced changes in the internal environment (i.e. accumulation of heat and metabolites, dehydration etc.) and changes within the muscle fibres (i.e. loss of excitability, reduction in calcium release from the sarcoplasmic reticulum, fuel availability etc.) [4]. Central muscular fatigue is a progressive reduction in the voluntary activation of muscle during exercise and is due to failures within the central nervous system; it occurs proximal to the neuromuscular junction such as within the motor cortex, spinal cord and motoneuron pool [4]. The technique of applying electrically evoked stimulation to the peripheral nerve is a commonly used technique to distinguish between central and peripheral muscular fatigue [5]. Figure 1.1 (taken from [6]) shows the chain of command of muscle contraction, from the motivation to contract, generated in the higher brain regions, down to cross-bridge cycling activity of the sarcomeres in the muscle fibres. Failures in the locations above the electrical stimulation arrow are potential sites of central fatigue, and below in peripheral fatigue.

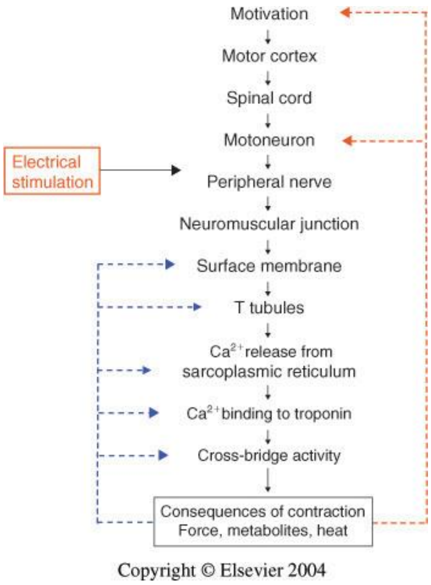


**Figure 1.1** The chain of command of muscle contraction (taken from [6])

### 1.1.2 Mental fatigue

Mental fatigue is defined as a psychobiological state that can be caused by engaging in demanding cognitive activity for a prolonged period and is often characterised by subjective feelings of tiredness and a lack of energy [7]. It has been associated with reduced accuracy [2], slower reaction time [8], and impaired workplace performance [9]. The underlying neural mechanisms have yet to be established [10]. Changes in neural activity associated with mental fatigue have been investigated in terms of cortical activity during the completion of tasks requiring a high level of cognitive processing [11]. Recently, multifactorial brain connectome approaches have been utilised, which employ multivariate functional connectivity analysis of neuroimaging to better understand the neural mechanisms underlying and identify the presence of mental fatigue [12]. The dual regulation system model of mental fatigue [10] proposes that a high cognitive demand activates both the mental facilitation and inhibition systems, and thereby causes mental fatigue. The mental facilitation system is an interconnecting neural circuit that connects the limbic system, basal ganglia, thalamus and frontal cortex. When motivation is high, the mental facilitation system is activated through increased dopaminergic drive, which increases effort and maintains cognitive task performance in the presence of a high mental demand. Over time this can cause dysfunction and induce a state of mental fatigue. The mental inhibition system comprises the insular cortex and posterior cingulate cortex, and activation can occur during any mentally demanding task, even those of low mental demand, and can impair cognitive task performance.

## 1.2 Mental fatigue and exercise performance

The last decade has witnessed extensive research on the impact of mental fatigue on subsequent endurance exercise performance, following on from the seminal study by Marcora and colleagues [7] in 2009. In this experiment a state of mental fatigue was induced using the 90-minute AX continuous performance (AX-CPT) test. The AX-CPT requires executive functions, such as attention, response inhibition, memory and error monitoring. In a subsequent submaximal cycling (80% peak power output) time to exhaustion test, task disengagement occurred almost two minutes (15% of control task duration) earlier when in a state of mental fatigue. Importantly, this mental fatigue-related performance impairment occurred with no differences in heart rate, stroke volume, cardiac output, mean arterial pressure, oxygen consumption, minute ventilation and blood lactate relative to a control condition. However, participants in the mental fatigue condition started the time to exhaustion test at a higher rating of perceived exertion (RPE). RPE increased similarly in both conditions as a linear function of time, and, therefore, the maximal tolerable level was reached earlier in the mental fatigue condition, leading to earlier task disengagement compared to the control condition. It was speculated that the elevated RPE was due to increased activity in the anterior cingulate cortex (ACC), since this brain region has been implicated in both cognitive and physical task performance [13] and ACC activity is positively correlated with RPE in both real and perceived exercise tasks [14,15].

In addition to whole-body endurance exercise, engagement in a prior cognitive task has also been shown to impair submaximal isometric muscular endurance performance. Bray and colleagues [16] reported that hold time on a 50% maximal voluntary contraction (MVC) isometric handgrip task was reduced after completing a short (3:40 minutes) incongruent Stroop task (endurance = 32 seconds) compared to a congruent Stroop task (endurance = 46 seconds). The incongruent Stroop colour-word test [17] activates the ACC, and involves working memory and response inhibition [18]. The impaired isometric muscular endurance performance was associated with increased forearm electromyography (EMG) activity, indicative of a higher drive to activate the muscle motor units to maintain the required force. A later experiment by the same research group [19] examined the dose-response relationship between the incongruent Stroop task and isometric handgrip exercise at 50% MVC. Their findings demonstrated that the cognitive task needed to last at least 4 minutes to impair the subsequent physical task performance.

The area of research on the impact of mental fatigue on physical activity should be of interest to anyone interested in optimising performance in roles with a high component of cognitive and physical activity such as the military, emergency services and even construction workers, in addition to the area of exercise performance. Accordingly, individuals should avoid mental fatigue when wishing to achieve optimal physical performance and performing activities associated with high cognitive and physical demands [20]. Mental fatigue has also been shown to impair skilled motor performance [21].

The above paragraphs summarise the main findings from the key research investigating the role of mental fatigue on exercise performance. The research following on from the studies by Marcora *et al.* and Bray *et al.* on the impact of mental fatigue on whole-body and muscular endurance exercise performance are summarised in table one. These studies will be discussed in more detail throughout the thesis chapters as they provide the background to the work conducted within this thesis. Additionally, the impact of mental fatigue on subsequent endurance exercise performance is summarised in a recent systematic review by Van Cutsem et al. [22]. Overall the evidence indicates that the negative effect of mental fatigue on subsequent submaximal whole-body endurance exercise is more likely to be accounted for by elevated RPE rather than cardiorespiratory and peripheral fatigue mechanisms [22–24] or changes in pacing strategies [25].

However, in contrast to muscular endurance and whole-body exercise, mental fatigue has been shown to have no impact on maximal anaerobic exercise. Evidence has established that performing a cognitive task does not affect subsequent maximal muscular contractions [26–29]. Additionally, countermovement jump and a 3-minute cycling time trial performance is reported to be unaffected when in a state of mental fatigue, despite an elevated RPE and reduced intrinsic task motivation [29]. This could be due to the differences in the predominant cause of fatigue between maximal and sub-maximal exercise. Specifically, sub-maximal muscular endurance activity is predominantly altered by central fatigue, whereas maximal muscular contractions are predominantly affected by peripheral fatigue [4]. Indeed, it has been demonstrated that mental fatigue does not reduce the ability of the central nervous system to recruit active skeletal muscle and should not be confused with central fatigue [28]. Maximal contractions and anaerobic activity require a high level of motivation to fully recruit the working muscle, whereas performance in submaximal endurance exercise can be affected by choices in pacing strategy. Pacing is how an athlete chooses to distribute their energy over the duration of an exercise task and can have a significant impact on performance [30]. Submaximal physical tasks that require optimal pacing also require an element of mental effort and self-control, which may be affected by a state of mental fatigue.

The evidence discussed above highlights the importance of mental fatigue in negatively affecting submaximal physical performance through increased perceived effort. Mental fatigue cannot affect peripheral physiological factors, or exacerbate central muscular fatigue, highlighting the role of the brain in regulating endurance exercise.

### 1.3 Brain regulation of endurance exercise

There are various models that attempt to describe and explain the role of the brain in the regulation of endurance exercise. Despite their differences, all now recognise the importance of perceived effort, emotion, and neural-cognitive processing as determinants of performance. This section will give a brief outline of the main models, their development and criticisms in order to better understand how mental fatigue can affect endurance exercise performance.

#### 1.3.1 Central governor model

In the 1996 J.B. Wolffe memorial lecture, Noakes questioned the traditional peripheral regulatory model of exercise and proposed an alternative based on the concept of central regulation which sowed the seeds of the central governor model [31]. The traditional peripheral model of fatigue was based upon the observation by Hill that during progressive exercise to exhaustion there is a plateau in oxygen consumption [32], limiting the supply of oxygen to the working muscles causing hypoxia and limiting performance. Noakes questioned this traditional view with three main arguments: 1) that there was limited evidence to support the oxygen plateau concept; 2) that there was no available evidence demonstrating skeletal muscle anaerobiosis develops during submaximal exercise at the anaerobic threshold, and 3) that alterations in metabolism and improvements in exercise performance can occur before mitochondrial adaptations, which cannot be explained by this model. To counter these claims he proposed an alternate model of active skeletal muscle regulation that operates by a series of neural and chemical regulators to prevent potentially fatal disturbances to physiological homeostasis during exercise in healthy and diseased conditions and under demanding environments such as extreme temperature and high altitude. This original proposal by Noakes of a central regulatory control system of skeletal muscle did not include reference to sensory feedback control or the generation of the perceived exertion, but which were added in subsequent iterations [33–35].

This, at the time, controversial view was counted with the criticisms that the failure to observe an oxygen plateau during incremental exercise testing is not the primary evidence for a cardiorespiratory limitation of exercise performance. Additionally, $VO_{2max}$ is the best predictor of athletic ability and is limited by anaerobiosis, and limited evidence was provided by Noakes to support his alternative proposal [36]. In his rebuttal to these criticisms Noakes points out that it was Hill who originally proposed the concept of a myocardium or nervous system governor mechanism that would terminate exercise before an oxygen consumption plateau caused myocardial damage [37]. Furthermore, he presented evidence demonstrating that cardiac output is not increased at any workload at altitude above that at sea level despite a reduced arterial oxygen content, again suggesting regulation by a governor system to prevent myocardial hypoxia. However, it was not until 2001 when the role of the brain was given more prominence as the regulatory centre linking cardiac function and exercise performance [38]. The basic premise of the original central governor theory proposes that a subconscious process in the brain integrates afferent sensory feedback from the heart, skeletal and respiratory muscles, and operates via the motor cortex to reduce the efferent neural activation of the exercising musculature to protect the heart from ischemia and prevents potentially fatal disturbances to physiological homeostasis.

In 2004 the central governor model was extended to account for the sensation of fatigue, which was proposed as the “sensory representation of the underlying neural integrative processes, rather than a defined and measurable physical event, that is a reduced skeletal muscle force output” [39]. Building on the theory of Ulmer [40], the concept of teleo-anticipation was added to the model to regulate exercise intensity at an acceptable level of fatigue with the exercise endpoint as the regulatory variable. Teleo-anticipation was originally defined as the “the changes in perceived exertion that result from these afferent signals may allow exercise performance to be precisely regulated such that a task can be completed within the biomechanical and metabolic limits of the body” [41]. It was proposed that exercise intensity is controlled as part of a pacing strategy involving active neural calculations in a ‘‘governor’’ region of the brain from the integration of internal sensory signals and environmental information. Evidence was also presented demonstrating that skeletal muscle is never fully activated during exercise, supporting the claim of efferent motor nerve restriction by the central governor [39].

Evidence in support of the concept of subconscious teleo-anticipation within the central governor model is often presented from deception studies [33]. Deception studies typically use a range of methodologies including manipulating the exercise intensity without informing the participant [42], withholding knowledge of endpoint [43] and creating uncertainty of the endpoint [44]. When participants are deceived about the length or intensity of exercise, they must complete it can cause changes in their subjective ratings of exertion. Proponents of the concept of subconscious teleo-anticipation regulating exercise intensity claim that this demonstrates that the brain generates the conscious perception of effort based upon the certainty of the duration and intensity of the exercise. An alternative explanation for these findings, is that uncertainty about the exercise requirements could cause a state of anxiety in the participants which raises their ratings of, or actual perceptions of physical effort. A later version of the central governor model [45] identified a range of factors (i.e. the presence of competitors, mental fatigue and music) which could potentially change a competitors psychological state, influence their perception of effort and as a result modify performance. The uncertainty of exercise may also operate in the same manner to adjust the perception of effort at each point in time, rather than altering its rate of progression in a subconscious anticipation of the endpoint.

The concept of subconscious teleo-anticipatory regulation within the central governor model was further included in later iterations of the model using the terminology ‘central controller’ [46,47], where was mainly based upon a series of cycling time trial experiments conducted in different ambient temperatures. The first of these investigated 20-km cycling time trial performance resulting in a reduction in overall power output and electromyographic muscle activity that progressively declined in the 35 °C trial relative to the 15 °C trial. [48]. This occurred despite similar core temperatures throughout the trial, apart from during the ‘end spurt’ in the final kilometre. Based upon this observation the authors attribute this finding to the teleo-anticipation of the central governor and restriction of efferent output to stop core body temperature from reaching dangerous levels. Additional support to the anticipatory regulation theory was provided in a similar study where participants were requested to cycle at a clamped RPE of 16 on the 6-20 Borg scale in a cool, neutral and hot environment until their power output fell to 70% of the first three minutes [49]. Power output declined at a higher rate in the hot condition despite similarities in heat storage. Finally, five cycling time trials were conducted in hot (35 °C) and cool (15 °C) conditions at a range of submaximal intensities (55% to 70% peak power output) to exhaustion [50]. As expected, RPE rose linearly as a function of time for all trials, but the rate of rise was higher in the two trials (cold 70% and hot 65%) with the highest intensity workloads. It was proposed that the rate of change in RPE is established in the brain, immediately upon the onset of activity, to allow for an appropriate duration of exercise so that it is terminated at the maximum tolerable exertion level but before the occurrence of catastrophic hyperthermia.

An alternative explanation for the above studies is that the perception of effort is increased when exercising in higher ambient temperatures simply due to the sensation of thermal discomfort generated from peripheral skin temperature sensors and a higher level of mental effort required to maintain the workload [51]. The rate of increase of RPE may not be set at the onset of exercise, but rather generated at each individual moment based upon the current and previous level of exertion and other psychological and physiological factors. The brain does not know (unless specifically told) that the exercise is to continue at the same intensity. Therefore, the setting of RPE at a specific rate of increase at the onset of exercise due to anticipatory factors seems illogical.

The diagram in Figure 1.2 (taken from [52]), shows the traditional Hill model based upon peripheral factors (top) and the contemporary central governor model (bottom).

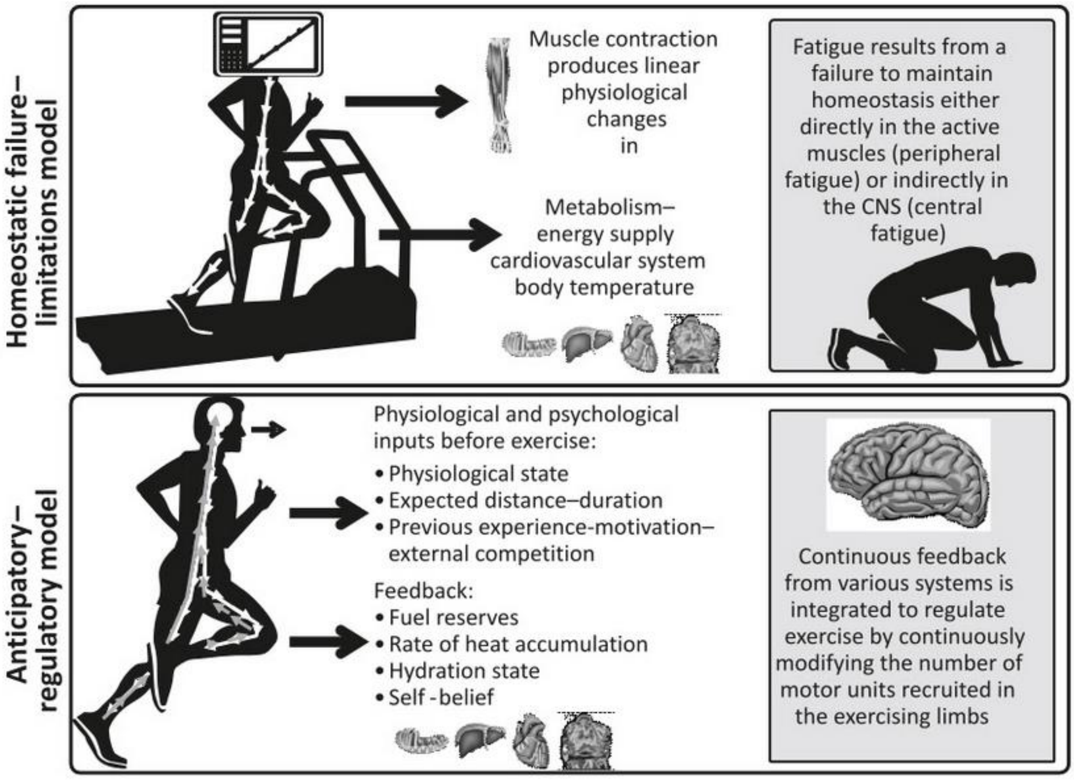


**Figure 1.2** The AV Hill and central governor models of exercise regulation (taken from [52])

A systematic review of the experimental findings of incremental exercise on cerebral oxygenation (measured by near-infrared spectroscopy) was evaluated considering the central governor model [53]. The authors proposed that a reduced cerebral oxygen saturation and blood volume during high intensity exercise, in people with a low aerobic capacity, is consistent with the central governor model. Moreover, it was proposed that repeated central nervous system exposure to a high neural input from fatiguing muscle afferents could desensitize the central governor, allowing for the maintenance of higher intensities of effort and a greater challenge to cerebral homeostasis among aerobically trained individuals. Alternatively, the differences in cerebral oxygenation between trained and untrained participants could be a result of cerebral changes and brain neuroplasticity due to physiological training adaptations.

In summary, all the evidence used in support of the central governor model is circular and circumstantial. Moreover, the evidence presented to support the central governor model is evidence that the brain regulates endurance exercise, not evidence of a subconscious governor limiting efferent outflow to exercising muscles to protect the body from fatal fluctuations to homeostasis. The central governor model has been regularly criticised by many prominent sports science researchers and exercise physiologists [54–57]. For example, Sheppard's main criticism stated that there was limited evidence for a central governor [56]. In rebuttal, Noakes summarised apparent contradictions in Sheppard's arguments by highlighting that he stated that there is no requirement, and no evidence, for a brain to regulate exercise but also stated that the brain's role in the regulation of exercise is so fundamental that additional investigation is unnecessary. In this defence, Noakes has confounded the role of the brain in exercise regulation and the central governor concept, which are not the same.

Noakes and colleagues have since acknowledged that the central governor model had previously neglected self-control, lacked integration of affective and emotional states, and was overly reliant on the role of perceived exertion [58]. In this advanced model, a centrally regulated and goal-directed three-dimensional framework of sensory, affective and cognitive processes was proposed. This latest iteration places perceived physical and mental strain as the primary components of the teleo-anticipatory pacing algorithm required to align planned behaviour with the person's physiological state. In addition, the person's psychological state and core affect mediates exercise performance and allows for behavioural modification within physiological boundaries.

### 1.3.2 Integrated governor model

St Clair Gibson is one of the main authors alongside Noakes who developed the central governor model. Alongside the experimental researchers, and proponents of the central governor model, Tucker and Swart, have recently proposed a new model of brain regulation of endurance exercise termed the *integrated governor model* [59]. This model proposes that traditional, central and peripheral concepts of fatigue are artificial constructs and that regulatory control is generated in a dynamic manner as a result of competition from psychological and physiological drives. The dynamic control builds upon the basic principles of maintaining homeostasis and negative feedback, and the general operational controller modifies efferent responses in comparison to a combination of prior information, current activity or activity templates. The model recognised and addressed criticisms of the original central governor model in that it lacked explanation of why exercise can be initiated in the presence of inhibitory warning signals so that it is sometimes possible to continue exercise to the point of fatal catastrophe. Moreover, the integrated governor model is based upon eight fundamental rules. *Rule one* states that exercise regulation, or choice in pacing output, is the result of competing protective physiological mechanisms and psychological goal-directed drives that are weighted based upon undetermined regulatory and algorithmic factors. The level of performance is the product of the continuous interplay of these opposing drives and dynamically changes over time. *Rule two* states that the same homeostatic control mechanisms can occur at any level of the physiological component and the system control operates upon a cascade of dynamic negative feedback loops. A negative feedback loop operates on the principle of a regulatory centre monitoring a setpoint register, based upon afferent feedback from a physiological system variable that modifies efferent output to select the current pace.

Building upon this proposal, *rule three* states that negative feedback loops are compared with metabolic set points to plan the adequate level of response. *Rule four* accounts for changes in the external environment such as knowledge of the endpoint and changes in ambient temperature to modify pacing output. If no such changes occur, then it is proposed that physical activity continues at the setpoint level. Due to the inherent time delay in physiological negative feedback loops, all subsequent decisions by the controller will be subject to periods of dynamic oscillation in uncertainty of the ability to process the required psychological and physiological information. This occurs both at rest and during exercise and is detailed in *rule five*. *Rule six* stipulates the unifying construct of system comparison in that changes in feedback from variables within the system must be compared with historical knowledge or predicted future requirements to enable adequate operation. *Rule seven* emphasises the importance of information processing across different system types and is a unifying factor of the integrated governor model. *Rule eight* outlines the sense of awareness of the perception of effort, which acts as an intermittent inhibitory sensation that competes with the psychological drive to continue with physical exertion. This final rules ends with the questionable suggestion that if you can accurately anticipate the level of fatigue required for an event then you should not be aware of the sensation of fatigue.

The contemporary central governor and integrated governor models have incorporated more psychological and social constructs and have advanced the role of the brain in regulating endurance performance. However, it has been highlighted that they have done little to aid sports psychologists in improving performance in an applied setting [60]. Additionally, they are both based upon the original concept of subconscious teleo-anticipatory generation of the rate of change in perceived exertion to regulate exercise intensity by restricting efferent motor recruitment to protect the body from fatal changes in homeostasis. The evidence provided to support this concept can be explained by simpler accounts such as thermal discomfort and psychological states which modify the perception of effort at each individual moment.

### 1.3.3 Psycho-biological model

The central governor theory was challenged in 2008 by Marcora who stated that it was internally inconsistent, unnecessarily complex, and biologically implausible; proposing the psychobiological model of endurance performance to explain the brain regulation of exercise [54]. This model states that fatigue is a conscious process and exercise will persist if the motivation (i.e. the reward of the activity, such as escaping from a dangerous situation, winning an Olympic medal) is greater than the perceived exertion (i.e. the physical discomfort generated from the activity) [61]. The psychobiological model proposes as the rate of change in the sensation of physical exertion can predict the point of exhaustion, it can be a unifying theory of exercise tolerance. The motivational aspect of this model is based upon Brehm's motivational intensity theory [62] and dictates that people will choose to disengage from a bout of exercise when the maximal effort that person is willing to exert is met, or when a maximal effort has been believed to have been exerted. The psychobiological model proposes that perceived exertion is the result of central processing of corollary discharge, generated as a result of motor neuron recruitment and projected to sensory areas of the cortex [63]. Therefore, the longer a physical activity persists, at the same workload, the greater the sense of effort becomes. Noakes's, rebutted the criticisms form Marcora, mainly based on the previously discussed experiments in support of subconscious teleo-anticipation and challenged the psychobiological model by questioning how the brain is made aware of the requirement to increase central motor command if afferent feedback is excluded [64].

In support of the concept of the central generation of the sense of effort, Marcora has presented evidence demonstrating that during whole-body endurance exercise it is independent of afferent feedback from skeletal muscle, heart and lungs [65] and that feedback from fatiguing muscles via group III and IV afferents is not an important determinant of endurance exercise performance [66]. In layman terms, the basic premise of this argument is that you can be tired at rest with no physical exertion is present, but to counter this argument, when you are tired physical tasks can seem more effortful.

### 1.3.4 Rate of perceived exertion

One of the main constructs the various models of brain regulation of exercise differ is in their proposal of the generation of the sense of effort during physical activity. Ever since the self-report of RPE during exercise was proposed by Borg in 1962 [67], it has become standard practice to obtain this measure within the field of sport and exercise science but still has the potential for further development [68]. The neurophysiological mechanisms for the generation of the sensation of effort and fatigue are not fully understood. There have been various proposals ranging from models based upon group III/IV afferent feedback [45], centrally generated from higher brain regions [54,61], and interactions between these two mechanisms [69] as presented in the previous sections. The relationships between RPE and physiological measures has been extensively researched finding the highest correlation with respiration rate [70] along with muscular sensations during cycling exercise [71]. It has been proposed [72] that respiration rate should be incorporated into athletes physiological monitoring alongside currently used power and heart rate measures.

Central command is commonly defined as the “feedforward mechanism involving parallel activation of motor and cardiovascular centres” [73] to evoke the initial cardiovascular response to exercise, has been shown to increase sweat rate [74] and is also linked to the perception of effort during exercise [75]. Central command originates from higher cortical regions, but these are difficult to identify during whole-body endurance exercise and Borg’s RPE scale often is used as a proxy for central command. The interactions between central command and other feedback components in the generation of the perception of effort have been proposed and are shown in Figure 1.3 (taken from [75]). In this diagram, the red arrows represent the generation of effort perception via central command, the blue arrows the further generation and influence via physiological feedback and other external and internal psychosocial factors are represented by the green arrows. The open arrows represent uncertain interaction issues such as, can effort perception; influence central command (A), effect the cardiovascular response to exercise independent of central command (B) and be influenced by anticipation of exercise (C).

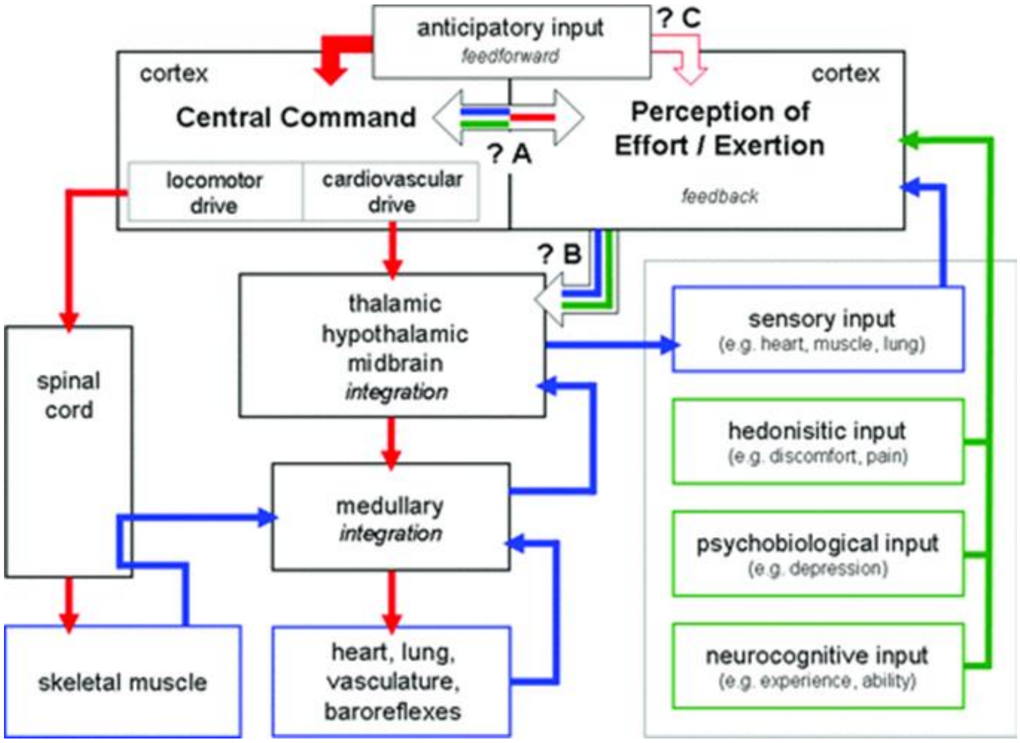


**Figure 1.3** the interaction of central command the perception of effort (taken from [75])

Afferent feedback from skeletal muscle, heart and lungs are integrated at the medulla oblongata which is a lower brain region located in the brainstem. The role of the midbrain regions have been implicated in the role of central command by investigations in a clinical demographic. In patients receiving deep brain stimulation in treatment for Parkinson's disease, globalised dystonia and chronic neuropathic pain neural cortical activity was measured in the subthalmic nucleus, globus pallidus interna and periaqueductal grey respectively during anticipated and very light cycling exercise (15 W) [76]. It was found that the periaqueductal grey and subthalmic nucleus are an important midbrain region in the neural circuitry of the cardiorespiratory response to the anticipation and actual exercise. The brain is a highly interconnected and complex organ and does not operate in isolation from its component parts. It is possible that the integration of afferent feedback at the lower brain regions can work through the midbrain and modulate the amount of central command required. When a person has high levels of peripheral fatigue, it is possible that increased feedback from group III/IV muscle afferents, increases the amount of central command required for a physical task, subsequently increasing the perception of effort required for a physical task relative to when not in a state of fatigue. This explanation, that the sense of effort is generated centrally, from higher cortical brain regions, but is modulated from feedback received at lower cortical regions explains why physical tasks seems more effortful when in a state of fatigue, even at their onset.

The separation of centrally generated effort and fatigue has become of increased importance and relevance following the debates discussed above regarding the various models of brain regulation of endurance exercise. Scales have been developed to measure fatigue in both everyday life situations and during maximal exercise [77], and a task effort and awareness scale [44] to determine the level of mental effort required to complete a physical task. These scales move away from Borg's RPE scales and can offer more insight to the subjective sensations of exertion and fatigue during endurance exercise.

### 1.3.5 Neurotransmitter hypothesis

The brain uses chemical neurotransmitters (acetylcholine, glutamate, aspartate, gamma-aminobutyric acid, dopamine, norepinephrine and serotonin) to communicate between brain cells. The neurotransmitter hypothesis postulates that fluctuations in levels of brain neurotransmitters during exercise and can influence fatigue during prolonged endurance exercise [78]. The neurotransmitter dopamine is associated with a willingness to exert effort, motivation and reward, and noradrenaline with attention and arousal. Serotonin is linked to depression and mood regulation. Increases in brain serotonergic activity during prolonged physical activity are associated with a concurrent augmenting lethargy and a loss of motivation which increases central fatigue and reduces motor unit recruitment of the contracting muscle [79]. However, there is a lack of compelling evidence to support this hypothesis with conflicting reports from research carried out using selective serotonin reuptake inhibitors drugs and branched chain amino acid supplementation in an attempt to change the levels of serotonin and influence performance [80]. However, changes in brain neurotransmitters do not happen in isolation are it is likely that there are fluctuations and interactions between them during prolonged exercise [81] but it is unknown if they are the cause of, or the result, of fatigue and exertion.

### 1.3.6 Strength control model

The models discussed above are form scientists who are predominantly and originally from an exercise physiology background. Recent interest in the role of the brain in regulation of endurance performance has come from psychologists who have built upon the strength control model. Self-control is the ability of an individual to regulate one's behaviours and responses in order to pursue long-term goals, and the term is often used interchangeably with self-regulation [82]. Self-control is proposed as a global psychological or cognitive resource requiring higher order executive processing such as, emotional and attention regulation, concentration and response inhibition, which can become depleted when utilised over time. The strength control model (also known as the strength-energy model) was originally proposed by Baumeister in 1994, and uses the analogy of self-control to a muscle [83]. As with a muscle, the more self-control is exerted the more fatigued it will become depleting an individual's global self-control resource. This reduces the ability of an individual to regulate their actions impacting on other activities that also require the global self-control resource. This effect is referred to as ego depletion, which is defined as a "temporary reduction in the self's capacity or willingness to engage in volitional action (including controlling the environment, controlling the self, making choices, and initiating action) caused by prior exercise of volition" [84]. Self-control is likely to be regulated by multiple interconnected psychological and physiological processes due to its complicated nature. Brief periods of rest, as short as 10 minutes, have been shown to replenish self-control resources and diminish the ego depletion effect [85]. Alongside regular brief periods of rest, and avoiding inadequate sleeping patterns, a common suggestion for the physiological mechanism underlying the strength control model is a reduction in blood glucose, where it is lowered following acts of self-control that is then associated with impaired performance on subsequent measures of self-control [86]. However, as experimental investigation into glucose supplementation on ego depletion has produced evidence both for [86] and against [87] this mechanism, and is still under debate [88]. A meta-analysis of 83 published research articles, which employed a 2-task paradigm, found a significant effect of reduced performance on the outcome task following the manipulation task with effect sizes for ego depletion on effort, perceived difficulty, negative affect, subjective fatigue, and blood glucose levels [89]. This has provided support for the strength control model hypotheses, alongside suggestions of motivation and fatigue as alternative explanations for the ego depletion effect. However, this meta-analysis has been criticised for including studies which were: low in ecological validity; had weak measures of self-control; had high confirmation bias as the experiments began with the premise that ego depletion was real [90], and as it only included published experiments was high in positive result publication bias [91]. Following these criticisms, a series of meta-analyses were conducted to address each of these points through stricter selection criteria and using contemporary statistical techniques to adjust for the influence of small study effects [92]. The analyses concluded that the ability to regulate self-control is not attenuated as it is used, that laboratory evidence for a global resource is limited, and that alternative theories should be considered in explaining the ego depletion effect [92]. Following these criticisms, the author of the original meta-analysis organised a multi-lab replication of a standardized 2-task paradigm protocol experiment with meta-analysis of the results failing to confirm the ego depletion effect [93]. In addition to these substantial issues regarding the effect size and replication of ego depletion, this area of research has been criticised for conceptual issues resulting from a lack of: clear and agreed definitions; independent verification for self-control tasks, and well specified models that make unambiguous and falsifiable predictions [94].

Initially, the strength control model and ego depletion effects have been investigated in areas such as racism, binge eating, substance abuse, unhealthy lifestyle habits and antisocial behaviour, but has recently been applied to the control of effort over exercise [95], which is a key component for successful performance [60]. As previously highlighted, the strength control model is not without its critics and limitations. However, there are aspects of the model and associated literature that may aid in both compliance to healthy physical activity and optimal exercise performance. The strength control model can provide a framework of recommendations through optimal nutrition, recovery, self-control training, and motivational and implementation intention strategies (such as contingency plans for certain events; i.e. if situation X occurs I will do action Y) to minimise any ego depletion effects and aid in successful adherence to exercise and training regimes [96], as well as habitual health-related physical activity [97].

In respect of these ongoing criticisms of the strength control model and its global resource based account to explain lapses in self-control and explanation of the ego depletion effect alternative motivational based perspectives have been put forward. In 2014, Inzlicht and colleagues proposed a model which is based upon motivational constructs and subsequent switching of task priorities rather than a limited global resource [98]. This motivational account of the ego depletion effect was proposed after several studies demonstrated that increases in motivation due a wide variety of manipulations including monetary rewards being offered to participants following a depletion task [99], affirming important core beliefs [100] and a the view that self-control is unlimited [101], increased performance on a subsequent performance task. The foundation of this alternative account is that failures in self-control are the result of evolutionary pressures, developing a motivation for individuals to balance desires for exploitation with exploration. In modern times, this further translates to a tendency for a person to seek equity with their 'have to goals' (a fundamental need to do things for oneself, such as work) and their 'want to' goals (a desire for leisure activity) as highlighted in figure 1.4. This model accounts for the ego depletion effect by claiming that once a large amount of cognitive effort is put into a laborious activity the motivation to continue engaging in it is diminished and motivation switches to leisure based activities, in order to balance mental work with mental rest. The negative change in emotions, interest and fatigue which develop during prolonged cognitive effort may have developed in order to redirect behaviours to ones which are inherently more enjoyable.

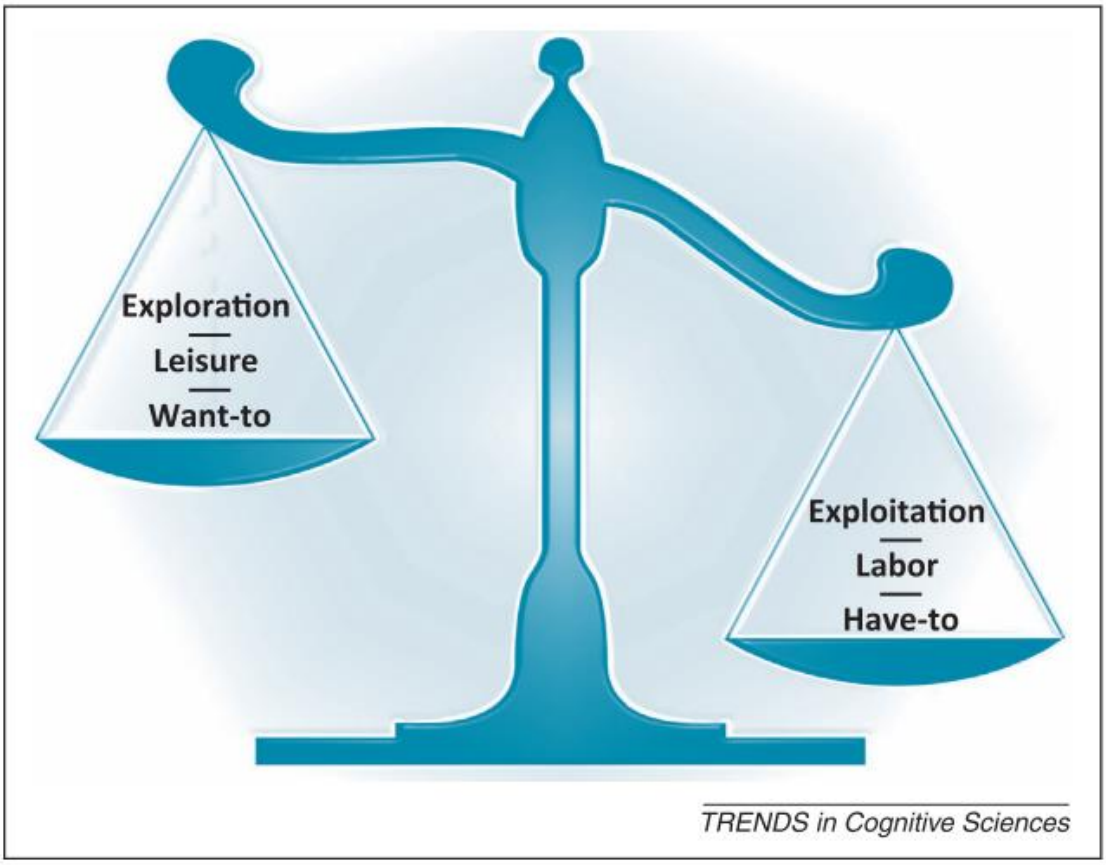


**Figure 1.4** the motivational account of self-control; the balancing of motivation inputs (taken from [98])

It has been proposed that self-regulatory fatigue and phsyical fatigue, in the context of the central govenor model, are the same phenoema potentially due to overlapping neural structures responsible for both constructs [102]. This leads to ‘crossover’ fatigue and can account for why mental fatigue impairs physical performance. However, considering the critiscms of the central govenor model previously presented, the balance between motivantional drives and physical exertion is accounted for by the pschobiological model of endurance performance in a simplier, more concise and testable manner.

### 1.4 Implications

This area of research has important real world applications, ranging from professional athletes who are looking to optimise every area of their performance to professions where people must conduct combinations of physical and cognitive tasks to a high level without one impacting on the other.

The studies presented, in support of the various models of brain regulation of endurance exercise, demonstrate that performance is often at a level lower than one is theoretically capable of. This raises questions as to the causes of the individual differences to the sensations of exertion and fatigue during exercise. For example, elite athletes have demonstrated an ability to withstand the negative effects of mental fatigue [103]. In terms of modifying submaximal exercise, any intervention, which can act centrally and lower perceived exertion for the same workload can potentially improve endurance performance.

It has been hypothesised that building resilience to mental fatigue and inhibition responses can attenuate the negative effects that they impose on exercise performance. This concept is referred to either brain endurance training, based on the psychobiological model of endurance performance,[104] or self-control training from the strength control model [105]. Brain endurance training could be either supplementary to, or completed alongside, existing training programs to provide an extra stressful stimulus onto an individual for them to improve physical and mental performance.

### 1.5 Research questions

The following section will summarise the main research questions that this thesis aims to address and a brief summary of the experimental chapters that aim to address them. Chapters two and three investigate mental fatigue and ego depletion using submaximal isometric exercise. Chapters four and five investigate mental fatigue and BET using a submaximal rhythmic muscular endurance task.

#### 1.5.1 Chapter two – ego depletion and isometric muscular endurance

The strength control model and ego depletion effect have been used to account for impairment in subsequent isometric handgrip performance following a brief cognitive task involving response inhibition. However, little is known about the dose-response relationship of the duration of cognitive task engagement and the deterioration in submaximal muscular endurance performance. The main aim of chapter one was to investigate this dose response relationship. Its secondary aims are to further examine the cognitive task performance as a function of time and application to a novel cognitive task. By examining cognitive performance further insight can be gained into the explanation of the strength control model, which proposes that engagement in tasks requiring self-control resources will deplete the global self-control resource and further impair subsequent tasks also requiring this resource. Consideration will be given to other models that may better account for improvements in cognitive performance as a function of time.

#### 1.5.2 Chapter three – mental fatigue and isometric muscular endurance

Mental fatigue is one component of the strength control model and ego depletion effect. Additionally, mental fatigue in isolation has been shown to impair submaximal endurance exercise. Both areas of research utilise the methodology of engaging in a cognitive task prior to a submaximal exercise test to investigate the phenomena. Cognitive tasks of 30 to 90 minutes in length are typically used to induce a state of mental fatigue when investigating its effects on whole-body endurance exercise. Brief cognitive tasks (less than 10 minutes) are typically used to deplete the global self-control resource and to investigate its impact on isometric muscular endurance. The experimental research investigating the impact of ego depletion and mental fatigue on subsequent exercise performance all use a mentally demanding cognitive task prior to the physical performance task, which require the executive response inhibition process. This makes it difficult to distinguish between these two phenomena. Response inhibition is defined as "the ability to suppress behaviours that are inappropriate, unsafe, or no longer required" [106]. The experiment in chapter two will separate the ego depletion effect from mental fatigue by using a cognitive task that does not require response inhibition to induce a state of mental fatigue and investigate its impact on isometric muscular endurance. The underlying physiological mechanisms mediating any performance changes, when in a state of mental fatigue, will be investigated by using near infra-red spectroscopy on prefrontal cortex cerebral haemodynamics and electromyographic muscle activity of the muscles used in handgrip contractions.

### 1.5.3 Chapter four – mental fatigue and dynamic muscular endurance

The evidence described above has established that a mentally-fatiguing cognitive task can impair endurance exercise. However, studies have yet to demonstrate the temporal effects of mental fatigue on subsequent exercise performance since previous experiments have all induced mental fatigue using a single task period. The importance of response inhibition during the cognitive task has yet to be established, despite being investigated in chapter three. The experiment in chapter four will address these gaps by comparing the effects of a series of bouts of cognitive tasks with and without response inhibition on self-paced rhythmic handgrip exercise and indices of mental fatigue. This experiment also investigates the effects of cognitive tasks on psychological and physiological measures during the endurance task as a function of time.

### 1.5.4 Chapter five – brain endurance training

It has been hypothesised that building resilience to the negative effects of mental fatigue can improve endurance performance. This is referred to as brain endurance training and is done by engaging in mentally demanding cognitive tasks during exercise. Only one study to date has demonstrated this effect and the underlying physiological mechanisms are unknown. The experiment in chapter five will investigate if brain endurance training enhances performance over matched physical training by using a six-week rhythmic handgrip training protocol. Potential physiological mechanisms will be investigated by using near infra-red spectroscopy on prefrontal cortex cerebral haemodynamics, electromyographic muscle activity of the muscles used in handgrip contractions and cardiac responses (heart rate and heart rate variability). Additionally, cognitive performance will be assessed by using both a task used during the brain endurance training protocol and a novel cognitive task that requires response inhibition to evaluate the efficacy of potential cognitive improvements due to brain endurance training.

| Study Title | Authors | Exercise | Design | Participants | Cognitive Task | Control Task | Physical Task | Outcome |
|---|---|---|---|---|---|---|---|---|
| Mental fatigue impairs physical performance in humans. | Marcora et al, 2009 [7]. | WBE | WS | 16 (10M, 6F) aerobically active 26 ± 3 years. | 90 mins AX_CPT test. | 90 mins emotionally neutral documentary. | Cycle time to exhaustion – 80% peak power output. | Reduced time to exhaustion relative (640 ± 316s) to control condition (754 ± 339s). |
| Impact of mental fatigue on self-paced exercise. | Brownsberger et al. 2013 [107]. | WBE | WS | 12 (8M, 4F) aerobically active. 24 ± 5 years. | 90 mins continuous performance test. | 90 mins emotionally neutral documentary. | 2 bouts of 10 minutes cycling at RPE 11 and RPE 15 in a randomised order. | Reduced power output at RPE 11 (83 ± 7 vs. 99 ± 7 W) and RPE 15 (132 ± 9 vs. 143 ± 8 W).<br><br>Greater EEG beta-band activation when mentally fatigued. |
| Response Inhibition impairs subsequent self-paced endurance performance. | Pageaux et al, 2014 [108]. | WBE | WS | 12 (8M, 4F) aerobically active 21 ± 1 years. | 30 mins incongruent Stroop test. | 30 mins congruent Stroop test. | 5 km treadmill run time trial. | Reduced time trial performance (24.4 ± 4.9 min) to control condition (23.1 ± 3.8 min). |
| Cognitive fatigue effects on physical performance during running. | MacMahon et al, 2014 [109]. | WBE | WS | 20 (18M, 2F) experienced runners 25.4 ± 3.24 years. | 90 mins AX_CPT test. | 3 min AX-CPT, 84 min documentary, 3 min AX_CPT. | 3 km run time trial. | Reduced time trial performance (12:11,88 min, SD =0:54,26) to control condition (11:58,56 min, SD =0:48,39). No difference in RPE between groups. |
| Emotion regulation and sport performance. | Wagstaff, 2014 [110]. | WBE | WS | 20 (10M, 10F) recreational endurance athletes 21.3 ± 1.61 years. | 1. 3 min Stroop + 3 min video (non-inhibition).<br><br>2. 3 min Stroop + 3 min video (emotional inhibition). | Control condition – straight to physical test. | 10 km cycle time trial with a fixed gear. | Suppression condition slower (M=18.42, SD=1.14) than control (M=17.82, SD=1.08). |
| Mental Fatigue Impairs Intermittent Running Performance. | Smith et al, 2015 [111]. | WBE | WS | 10M recreational intermittent activity team sport players. 22 ± 2 years. | 90 mins AX_CPT test. | 90 mins emotionally neutral documentary. | 15 x 3 minutes of random bouts of: stand, walk, jog, run, fast run, and sprint. | Lower running velocities in the low intensity bouts when in a state of mental fatigue. No changes in the higher intensities. |
| Mental Fatigue Impairs Soccer-Specific Physical and Technical Performance. | Smith et al, 2016 [112]. | WBE | WS | 12M moderately trained soccer players 24.0 ± 0.4 years. | 30 mins incongruent Stroop test. | 30 mins reading magazines. | Yo-Yo Intermittent Recovery Test, Level 1. | Lower amount of distance covered when in a state of mental fatigue (1203 ± 402 m relative to 1410 ± 354 m).<br><br>An additional experiment in this paper demonstrates reduced soccer skill performance when in a state of mental fatigue. |
| Effects of mental fatigue on endurance performance in the heat. | Van Cutsem et al. 2017 [113] | WBE | WS | 10M recreational | 45 mins 50% incongruent Stroop task plus 5 min flanker task | 45 mins emotionally neutral documentary | 45 min cycling at 60% Wmax and time trial at workload set at the | No difference in time trial performance. |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | cyclists 22 ± 3 years. | | plus 5 min flanker task. | equivalent of 80% Wmax workload in 30 °C. | |
| Application of the limited strength model of self-regulation to understanding exercise effort, planning and adherence. | Ginis & Bray, 2009 [114]. | WBE | BS | 61 university students, low activity level.<br><br>Do not regularly cycle. 20.0 ± 2.4 years. | Incongruent Stroop test – 3 mins 40 seconds. | Congruent Stroop – 3mins 40 seconds. | 15 min cycle at ‘heavy’ (5/10 Borg) intensity. Total work completed compared. | Lower level of work (-5.23 kJ, SD=7.48) on second bike ride in depleted relative to control (-2.8 kJ, SD=7.49) condition but not statistically significant.<br><br>No difference in mood states between groups after manipulation. |
| Effects of self-regulatory strength depletion on muscular performance and EMG activation. | Bray et al, 2008 [16]. | ISO | BS | 49 sedentary students (35F, 14M) 21.25 ± 1.70 years. | 3mins 40seconds Incongruent Stroop test. | 3mins 40seconds Congruent Stroop test. | 50% MVC isometric handgrip. | Time to failure decreased from 42s to 32s from pre to post manipulation handgrip in incongruent condition.<br><br>Time to failure increased from 44s to 46s in control condition. |
| Cognitive task performance causes impaired maximal force production in human hand flexor muscles. | Bray et al, 2012 [115]. | ISO | BS | 38 sedentary university students (F23, M15) 21.47 ± 3.16 years. | 1x 45 second + 7x 2mins 45 seconds Incongruent Stroop test. | 1x 45 second+ 7x 2mins 45seconds Congruent Stroop test. | 8x 100% 4 second MVC isometric handgrip. | Linear reduction in MVC force overtime in inhibition condition, no change in control.<br><br>RPE higher in each of the 8 physical tasks due to inhibition. |
| Prolonged mental exertion does not alter neuromuscular function of the knee extensors. | Pageaux et al, 2013 [26]. | ISO | WS | 10 healthy and active males 22 ± 2 years. | 90 mins CPT- AX test. | 90 mins emotionally neutral documentary. | 1. MVC knee extensors.<br><br>2. 20% MVC knee extensors – endurance task. | 1. Similar decrease in MVC in both conditions.<br><br>2. Time to exhaustion 13% ± 4% shorter due to mental fatigue. |
| Does mental exertion alter maximal muscle activation? | Rozand et al, 2014 [27]. | ISO | WS | 10 healthy and active males 24.5 ± 1.4 years. | 10x 3 mins incongruent Stroop test (high mental exertion). | 1. 10x 3 min Congruent Stroop (moderate mental exertion).<br><br>2. 10x 3 min movie (low mental exertion). | 10x electrical nerve simulation MVC of knee extensors.<br><br>Each MVS post 3 minute manipulation. | No difference in maximal voluntary torque and maximal muscle activation similar amongst conditions. |
| Investigating the effects of ego depletion on physical exercise routines of athletes. | Dorris et al, 2011 [116]. | REX | WS | 1. 24 competitive rowers (M).<br><br>2. 24 (8M, 16F) club level rugby / hockey players. | 1. Count down from 1000 in 7’s, standing on one leg.<br><br>2. Count down from 1000 in 7’s, standing on one leg. | 1. Count down from 1000 in 5’s + non fatigue balance task.<br><br>2. Count up to 1000 in 5’s + non fatigue balance task. | 1. Number of press ups.<br><br>2. Number of sit-ups. | 1. Decrease from 30 to 26 press ups completed following the more difficult arithmetic task.<br><br>2. Decrease of 146 to 110 sit ups completed following the more difficult arithmetic task. |

**Table 1**: Cognitive fatigue effects on exercise performance. (WBE: Whole body endurance, ISO: Isometric, REX: Resistance exercise, WS: Within-subject, BS: Between-subject.

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2

# Ego depletion and isometric muscular endurance

## 2.1 Abstract

**Introduction:** Brief (<4 minutes) response inhibition tasks has been shown to impair isometric muscular endurance and is often attributed to the strength control model. This model hypothesises that tasks requiring global self-control resource will impair performance on subsequent tasks also requiring self-control (ego depletion). However, time on task improvements have challenged the strength control model hypothesis and the cognitive control theory has been proposed to account for the ego depletion effect

**Objectives:** Investigate: 1) the dose-response relationship of the duration of a cognitive response inhibition task on subsequent muscular endurance performance. 2) the performance on the cognitive task as a function of task duration. 3) the effects of the duration of a cognitive task on a subsequent novel cognitive task performance.

**Methods:** In a multi-factorial between-participant (n=180) experimental design with two factors: colour word Stroop task (incongruent, congruent) and time (5, 10, 20 minutes) participants completed a colour word Stroop task, an isometric handgrip to exhaustion at 30% maximal voluntary contraction (MVC) and a five minute novel cognitive task (incongruent number Stroop) Measures of motivation, fatigue and physical and mental exertion were collected throughout.

**Results:** Physical handgrip performance deteriorated ($p<.05$) in the 10 minute incongruent group (130 s) relative to the congruent (180 s) In the 20 minute group, the incongruent condition demonstrated time on task improvements in reaction time not seen in the congruent group. In the novel cognitive task, participants in the incongruent condition were more accurate (88.0%) in their responses that the congruent (86.6%) ($p<.05$)

**Conclusion:** 10 minutes of engagement in a response inhibition task impaired subsequent isometric handgrip endurance performance at 30% MVC, but tasks of 5 and 20 minutes in length had no effect. Learning effects were observed during the 20 minute incongruent cognitive task. Completing a prior cognitive response inhibition task improved a novel cognitive response inhibition task completed several minutes later. These results are not predicted by the strength control model and are better explained by cognitive control theory.

## 2.2 Introduction

Self-control is the ability of an individual to regulate one's behaviours and responses in order to pursue long-term goals and the term is often used interchangeably with self-regulation [1]. Self-control is proposed as a global psychological or cognitive resource requiring higher order executive processing such as, emotional and attention regulation, concentration and response inhibition, which can become depleted when utilised over time. The strength control model (also known as the strength-energy model) was originally proposed by Baumeister in 1994 and uses the analogy of self-control to a muscle [2]. As with a muscle, the more self-control is exerted the more fatigued it will become depleting an individual's global self-control resource. This reduces the ability of an individual to regulate their actions impacting on other activities that also require the global self-control resource. This effect is referred to as ego depletion and is defined as a "temporary reduction in the self's capacity or willingness to engage in volitional action (including controlling the environment, controlling the self, making choices, and initiating action) caused by prior exercise of volition" [3]. Self-control is likely to be regulated by multiple interconnected psychological and physiological processes due to its complicated nature. Brief periods of rest, as short as 10 minutes, have been shown to replenish self-control resources and diminish the ego depletion effect [4]. Alongside regular brief periods of rest and avoiding inadequate sleeping patterns a common suggestion for the physiological mechanism underlying the strength control model is a reduction in blood glucose following acts of self-control which has been associated with impaired performance on subsequent measures of self-control [5]. However, as experimental investigation into glucose supplementation on ego depletion has produced evidence both for [5] and against [6] this mechanism, and is still under debate [7].

Ego depletion is typically investigated using a 2-task paradigm, where participants are required to complete 2 sequential tasks both of which require self-control. The first task is often a manipulation task that is assumed to deplete the global self-control resource by a varying amount. Performance is measured on the subsequent outcome task to determine the amount of ego-depletion that has occurred. The 2-task paradigm experiments often utilise tasks from different disciplines (i.e. cognitive, physical, emotional restraint, impulse control etc.) to test the concept of self-control being a global resource. A major criticism of both the glucose-strength control model and 2-task paradigm from differing domains was raised by Lange and colleagues in a pair of experiments which used the same task, as both the manipulation and outcome task, and found no effect of ego depletion [6]. Using tasks from the same domain was criticised for a failure to control for cognitive learning effects, increased boredom, low levels and a lack of motivation to exert self-control throughout the tasks, and it was suggested that "the methodology of using the same self-control task twice should be interpreted with caution when researchers test the ego-depletion effect and the glucose hypothesis" [8]. This criticism was refuted by Lange stating that a prediction of the strength control model is that the global self-control resources should become more depleted as they are expended regardless of the task domain, and that if ego depletion cannot be investigated by tasks from the same domain then it is not ego depletion [9].

However, most of the research into ego depletion is carried out with tasks from separate disciplines. A meta-analysis of 83 published research articles, which employed a 2-task paradigm, found a significant effect of reduced performance on the outcome task following the manipulation task with effect sizes for ego depletion on effort, perceived difficulty, negative affect, subjective fatigue, and blood glucose levels [10]. This has provided support for the strength control model hypotheses, alongside suggestions of motivation and fatigue as alternative explanations for the ego depletion effect. However, this meta-analysis has been criticised for including studies which were: low in ecological validity; had weak measures of self-control; had high confirmation bias as the experiments began with the premise that ego depletion was real [11], and as it only included published experiments was high in positive result publication bias [12]. Following these criticisms, a series of meta-analyses were conducted to address each of these points through stricter selection criteria and using contemporary statistical techniques to adjust for the influence of small study effects [13]. The analyses concluded that the ability to regulate self-control is not attenuated as it is used, that laboratory evidence for a global resource is limited and that alternative theories should be considered in explaining the ego depletion effect [13]. Following these criticisms, the author of the original meta-analysis organised a multi-lab replication of a standardized 2-task paradigm protocol experiment with meta-analysis of the results failing to confirm the ego depletion effect [14]. In addition to these substantial issues regarding the effect size and replication of ego depletion, this area of research has been criticised for conceptual issues resulting from a lack of: clear and agreed upon definitions; independent verification for self-control tasks, and well specified models that make unambiguous and falsifiable predictions [15].

Initially, the strength control model and ego depletion effects have been investigated in areas such as racism, binge eating, substance abuse, unhealthy lifestyle habits and antisocial behaviour but has recently been applied to the control of effort over exercise [16], which is a key component for successful performance [17]. As previously highlighted, the strength control model is not without its critics and limitations, however there are aspects of the model and associated literature that may aid in both compliance to healthy physical activity and optimal exercise performance. The strength control model can provide a framework of recommendations through optimal nutrition, recovery, self-control training, and motivational and implementation intention strategies (such as contingency plans for certain events, i.e. if situation X occurs I will do action Y) to minimise any ego depletion effects and aid in successful adherence to exercise and training regimes [18] as well as habitual health related physical activity [19]. In addition, the acute effects of ego depletion on subsequent exercise performance have been researched using the 2-task methodology on exercise performance (outcome task) following activities requiring self-control (depletion task). Within the field of exercise and physical activity this is usually done with a cognitive response inhibition task as the depletion task followed by a physical task requiring a high level of focus and effort to complete at a high performance. Bray and colleagues [20] demonstrated a reduction in submaximal isometric handgrip time to exhaustion task of 43% following a brief (220 s) incongruent colour word Stroop task relative to a non-response-inhibition congruent version of the same task, and attributed these findings to the strength control model and ego depletion effect. The same research group conducted a similar follow up experiment [21] with further examination of the dose-response relationship between the length of engagement in an incongruent Stroop task and capacity to conduct an isometric handgrip exercise at 50% maximum voluntary contraction (MVC). The results indicated that the cognitive response inhibition task needed to last at least 4 minutes to impair subsequent physical task performance.

If depleting cognitive self-control tasks can impair exercise-related self-control performance, then it is logical to assume the reverse. The first study to examine this was also conducted by Bray and colleagues [22], who examined the dose-response of the intensity (30%, 50% and 70% MVC) of an isometric handgrip task to exhaustion on cognitive performance during 10 minutes of an incongruent Stroop task. Results showed an overall improvement in cognitive performance relative to baseline following the handgrip task. The cognitive task performance improvements degraded in a linear fashion with increased preceding exercise intensity. The overall cognitive improvements following a physical task that requires a high level of self-control resources appears to contradict the strength control model. As the cognitive task improvements were also seen in a control group, who held the handgrip at 5 N for 4 minutes, this was attributed to cognitive task learning effects. Another criticism of 2-task paradigm experiments is that they focus on performance in the outcome task and often neglect performance in the manipulation task [23]. It is logical to assume that if the manipulation task is depleting an individual's global self-control resource then performance should decline as a function of time. If performance is improving in the depletion task, then it is reasonable to question if the global self-control resource is being depleted and why should performance decline in the following outcome task? Adaptation to the Stroop interference effect has been demonstrated by Dang and colleagues [24], who found a positive correlation between the Stroop interference effect during prolonged engagement in and the number of errors committed in a subsequent 5-minute attention task in the depletion condition, which was also consistent with this idea. The adaptation to a self-control cognitive task was attributed to the cognitive control theory [25], which was also proposed as an explanation of the ego depletion effect. The cognitive control theory proposes that the cognitive system monitors for response conflicts and recruits additional resource when this occurs allowing adjustment to situational demands and can explain improvements in performance as time on task increases. In the 2-task paradigm experiments, when the participants undertake the subsequent self-control outcome task in a new domain it takes a short time period for cognitive resources to adjust to the new task resulting in an inferior performance.

In addition to the strength control model and cognitive control theory, the role of mental fatigue has been raised as an alternative explanation for the ego depletion effect [26]. Mental fatigue is defined as a psychobiological state that can be caused by engaging in demanding cognitive activity for a prolonged period, and is often characterised by subjective feelings of tiredness and lack of energy [27]. Research in the past decade has investigated the role of mental fatigue on subsequent whole-body exercise performance and has been summarised in the review by Van Cutsem and colleagues [28]. This review concludes that the negative effect of mental fatigue on subsequent submaximal whole-body endurance exercise is more likely to be accounted for by elevated ratings of perceived exertion (RPE) rather than cardiorespiratory and peripheral fatigue mechanisms.

In summary, there is ambiguity on the impact of task domain on investigating ego depletion when using the 2-task methodology, the function of time on task on response inhibition tasks on cognitive performance, and subsequent physical task performance and transfer of task adaptation. There are substantial criticisms and limitations of the strength control model, its root causes and the alternative cognitive control model has been proposed to account for the ego depletion effect as well as time-related improvements on tasks from the same domain. The development of mental fatigue could also impair task performance and account for the ego depletion effect.

### 2.2.1 The present study

The present study was designed to address the limitations discussed above, investigate potential learning effects (or decline in performance) due to prolonged engagement in a cognitive depletion task, and investigate the possible transfer of adaptation to response inhibition tasks from one domain to another. To do this we employed a triple task design. There are very few studies that have used a triple task design to investigate the ego depletion effect. When more than 2 tasks have been investigated the first task is usually for baseline measures to be collected, such as in the previously described studies by Bray and colleagues, rather than to investigate performance outcomes. If self-control resources are reduced due to a depletion task and impair outcome task performance, then according to the strength control model it should further impair performance in a second outcome task. In our triple task design the initial cognitive depletion task was of a variable duration and involved response inhibition in the experimental groups. This was then followed by 2 fixed length outcome tasks, the first in the physical domain and the second in the cognitive domain. The final cognitive outcome task involved response inhibition, as in the initial depletion task, but was novel to all participants. Performance measures will be investigated in both the depletion and outcome tasks and ratings of mental fatigue and mental exertion taken following each task. We have based our hypothesis on the assumption that the ego depletion effect is due to a reduction in global self-control resource as time on task increases and as a result all performance measures will decrease as a function of time.

This study has three specific aims. The first aim is to investigate the dose-response relationship concerning the effect of the duration of a cognitive response inhibition task on subsequent muscular endurance performance. It was hypothesised that cognitive task duration would be inversely related to subsequent muscular endurance. The second aim is to investigate performance on the cognitive task as a function of task duration. It was hypothesised that performance would decrease with time. The third aim is to investigate the effects of the duration of a cognitive task on a subsequent novel cognitive task performance. It was hypothesised that cognitive task duration would be negatively related to performance on the subsequent novel cognitive task.

## 2.2 Methods

### 2.2.1 Participants

Participants were 180 (77 females, 103 males; aged 18.79 ± 1.43 years) healthy undergraduate students volunteers who received course credit for participation. They were asked to abstain from vigorous exercise and alcohol, and to have a regular night's sleep in the 24 hours before testing. They were also asked to refrain from eating (one hour) and consuming caffeine (three hours) before testing. Ethical approval for the study was obtained from the local ethics committee and participants provided written informed consent.

### 2.2.2 Experimental design and procedure

The study employed a multi-factorial between-participant experimental design with two factors: task (incongruent Stroop, congruent Stroop) and time (5, 10, 20 minutes). Participants attended one laboratory session. Participants were asked to remain seated on a stool throughout and face a computer monitor positioned at eye level 1 metre away. After obtaining the participant's maximal voluntary contraction (MVC) grip force (see section 2.2.3), they were randomly allocated to one of six groups, which differed in terms of task and duration (see section 2.2.4). To increase task motivation, performance scores were displayed on a whiteboard. Each group completed their cognitive task for 5, 10 or 20 minutes followed by a submaximal isometric handgrip task (see section 2.2.5). Finally, participants completed a novel 5-minute cognitive task (see section 2.2.6). Participants provided psychological state ratings before and after each task (see section 2.2.7). The experimental procedure is shown in Figure 2.1.

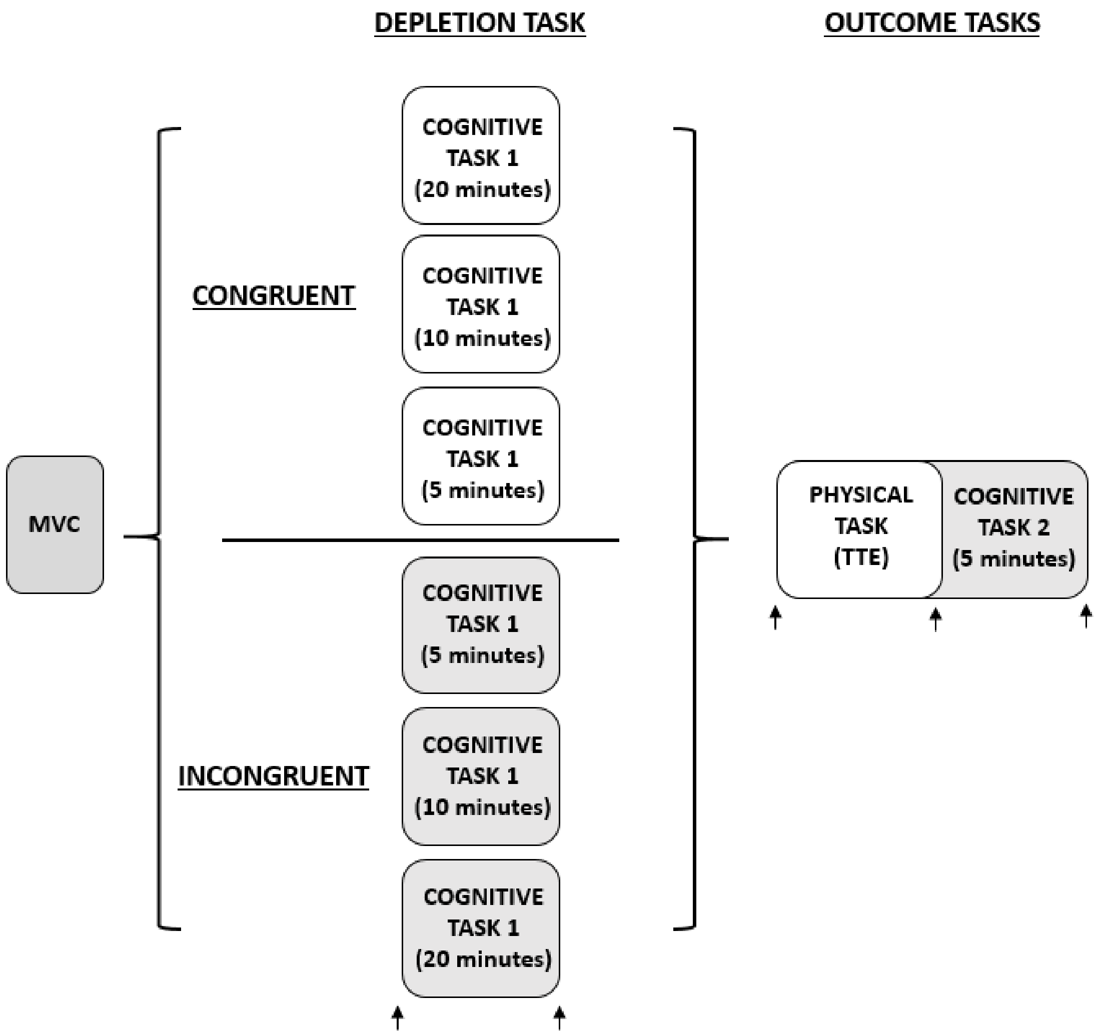


**Figure 2.1** Experimental Protocol. (Arrows indicate ratings questionnaires, TTE: Time to exhaustion)

### 2.2.3 Maximum voluntary contraction

Participants were instructed to squeeze a handgrip as hard as possible for several seconds in order to obtain their MVC [29]. They were not aware that the MVC informed the subsequent physical tasks. Participants held a bespoke handgrip dynamometer [30] in their dominant hand, placed on their knee, with their arm flexed at approximately 100 degrees. Participants performed a maximal contraction of the handgrip dynomometer and the peak force was recorded. This was repeated three times, with each contraction separated by a 1-minute rest to allow for recovery; the largest peak force achieved was recorded as the MVC. If the second highest peak force was not within 5% of the highest, another contraction was required.

### 2.2.4 Cognitive task

The cognitive task was the congruent or incongruent colour word Stroop task, performed for 5, 10 or 20 minutes. The colour word Stroop [31] required participants to indicate the font colour (red, blue, green and yellow) of a colour word from two possible answers displayed in a black font in the bottom left and right corners of the display with a corresponding left (Z) or right (/) keyboard button press. Participants received verbal and written instructions (Figure 2.2) prior to the task.

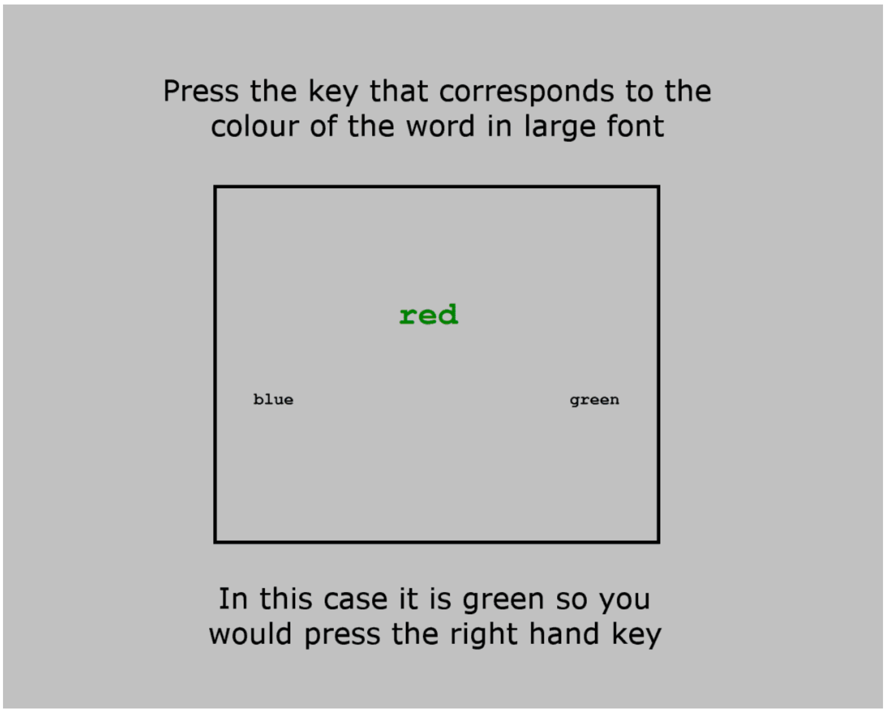


**Figure 2.2** Incongruent colour word Stroop task instructions

In the congruent task, the word was displayed in the same colour as its meaning, whereas in the incongruent task they were different. Only the incongruent Stroop task requires response inhibition and working memory [32]. Performance was measured by response time (ms) and accuracy (% correct). For both Stroop tasks the stimulus was presented for 2500 ms or until a response was made, followed by a fixation cross for 500 ms.

### 2.2.5 Handgrip task

The physical task required participants to maintain an isometric hold of the handgrip dynamometer with their dominant hand at 30% of their MVC for as long as possible. Visual feedback was given to participants via a single 40 mm wide by 55 mm high dual-colour (green, red) 7-segment light emitting diode panel that indicated the percent of their MVC, above or below the 30% threshold, their current grip force represented. Green numbers indicated a force equal to, or greater than, 30% MVC, whereas red numbers indicated a force less than 30% MVC. Participants were instructed to maintain a grip force that ensured a low green number for as long as possible. Task performance was determined by the duration of the isometric hold and was measured from task onset to the point when grip force fell below 30% MVC for more than two seconds. Figure 2.3 shows the physical task setup.

All force data (for the MVC and physical task) were acquired via a Power 1401 (Cambridge Electric Design Limited, UK) multi-channel analogue-to-digital convertor (16-bit resolution at a sampling rate of 2.5 kHz) and the output continuously recorded on a computer using Spike 2 software (version 6.06).

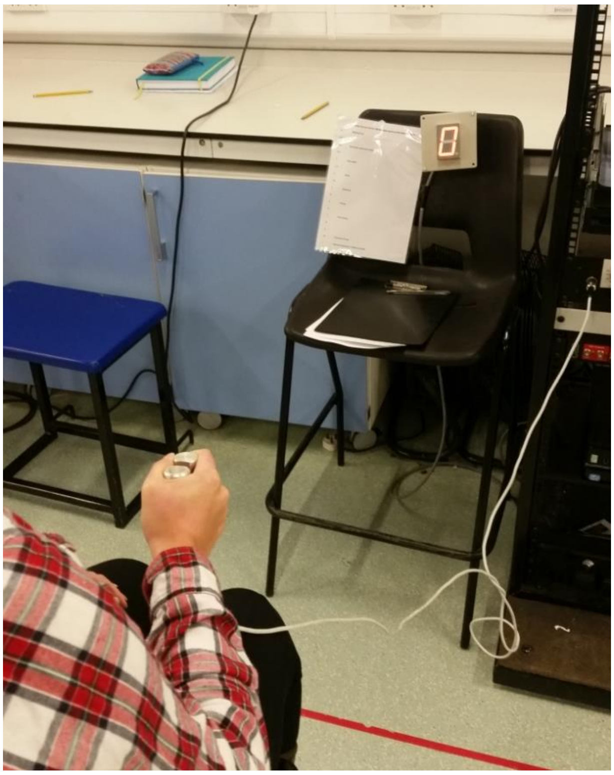

**Figure 2.3** Physical handgrip task

### 2.2.6 Novel cognitive task

Following the physical task, participants completed a 5-minute number incongruent Stroop task. Participants were required to indicate how many words were displayed from a list of number words (between one and four) of the same type (e.g. two, two, two); the correct answer was the number of words in the list (e.g., three) whereas the incorrect answer included the number that the words represented (e.g., two). The two possible answers (e.g., 'two' or 'three') were displayed in black font in the bottom left and right corners of the display, and participants responded with either a left (Z) or right (/) keyboard button press. Participants received verbal and written instructions (Figure 2.4) prior to the task. Performance was measured by the response time (ms) and accuracy (% correct).

Both cognitive tasks were implemented with E-Studio (version 2.0.1.97, Psychology Software Tools, Inc., USA).

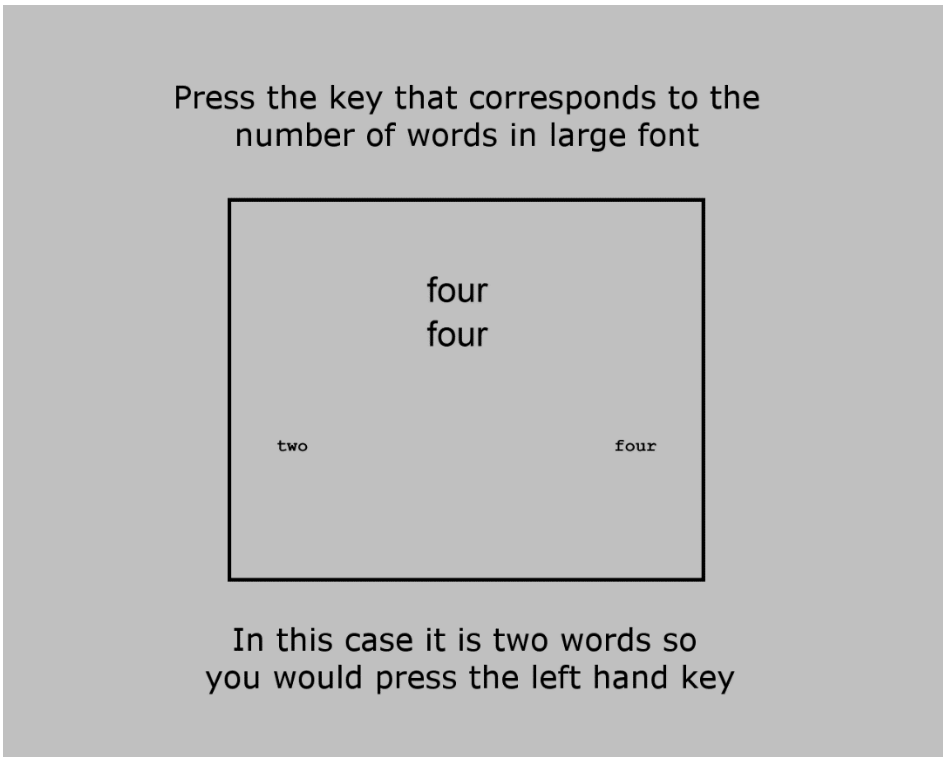


**Figure 2.4** Incongruent number Stroop task instructions

### 2.2.7 Psychological state measures

#### 2.2.7.1 Fatigue and exertion

The cognitive tasks were rated immediately following completion for mental exertion (ME) and mental fatigue (MF) on 10-point category ratio (CR-10) scales. The ME scale was anchored with the extreme descriptors “nothing at all” and “maximal mental exertion”. The MF scale was anchored with the extreme descriptors “nothing at all” and “totally exhausted”. Participants were reminded that these scales related to mental tiredness and exertion and not physical sensations. Following the cognitive and physical task, items (exhausted, sleepy, tired, worn-out) from the fatigue subscale of the profile of mood states (POMS) were rated on a 5-point scale with anchors of 1 “not at all” and 5 “extremely” [33]. Ratings of perceived exertion (RPE) were given verbally immediately at task failure on a 10-point CR-10 scale [34], anchored with the descriptors “nothing at all” and “maximal”. The standard instructions for the scale [35] were read to participants prior to each physical task.

#### 2.2.7.2 Interest and enjoyment

Task interest and enjoyment was measured using the interest/enjoyment subscale of the intrinsic motivation inventory [36]. Participants were presented with seven items (e.g., “I enjoyed doing this activity very much”, “I would describe this activity as very interesting”), and responded on a 7-point scale, with anchors of 1 “not true at all” and 7 “very true”.

### 2.2.8 Statistical analysis

Statistical analysis was carried out using SPSS 24 software (SPSS: An IBM Company, Chicago, IL, United States). Statistical significance was set at $p \leq .05$. All data values were expressed as mean ± standard deviation of the mean (M ± SD) unless otherwise stated. Partial eta-squared ($\eta_p^2$) was reported as the effect size, with values of 0.02, 0.13 and 0.26 indicating small, medium and large effects, respectively [37]. All ANOVA tests were implemented with sex as a covariate to control for the slight imbalances in the number of males and females in each group. Significant ANCOVA effects were followed by least significant difference (LSD) post-hoc tests.

## 2.3 Results

### 2.3.1 Handgrip task performance

Performance on the word Stroop task, physical task, and number Stroop task are shown in Table 1. A 2 group (incongruent, congruent) by 3 time (5, 10, 20 minutes) ANCOVA on grip hold duration in the physical task yielded a group main effect, $F_{1,173}$ = 3.90, $p \leq .05$, $\eta^2 = .02$, and a group-by-time interaction effect, $F_{2,173}$ = 3.29, $p < .05$, $\eta^2 = .04$. Endurance time was approximately 12% shorter after the incongruent Stroop (152.90 ± 63.39 s) compared to the congruent Stroop (173.17 ± 75.32 s). As can been seen in Table 2.1, endurance was only shorter following incongruent Stroop compared to congruent Stroop when the tasks were 10 minutes in duration.

A 2 group (incongruent, congruent) ANCOVA, with sex as a covariate, on the MVC yielded no group differences, $F_{1,177}$ = 3.50, $p > .05$, $\eta^2 = .02$, between the incongruent ($M$ = 438.98 ± 112.58 N) and congruent groups ($M$ = 428.71 ± 98.78) in handgrip strength.

| | | Colour Word Stroop Task | | Physical Task | Number Word Stroop Task | |
|---|---|---|---|---|---|---|
| Duration | Group | Correct (%) | RT (ms) | Time (s) | Correct (%) | RT (ms) |
| 5 | Congruent | 97.20 ± 1.83 [a] | 594 ± 83.60 [c] | 161.56 ± 56.30 | 87.57 ± 3.07 | 888.90 ± 134.16 |
| | Incongruent | 95.20 ± 3.00 [a] | 884.87 ± 144.19 [c] | 150.82 ± 62.65 | 88.00 ± 3.13 | 860.53 ± 105.48 |
| 10 | Congruent | 95.43 ± 2.81 | 595.20 ± 75.00 [c] | 186.21 ± 69.22 [a] | 86.03 ± 3.87 [a] | 864.80 ± 130.03 |
| | Incongruent | 95.87 ± 2.65 | 833.87 ± 144.99 [c] | 129.97 ± 49.43 [a] | 88.17 ± 2.07 [a] | 858.90 ± 99.98 |
| 20 | Congruent | 96.23 ± 3.18 [b] | 580 ± 94.65 [c] | 171.73 ± 95.59 | 86.23 ± 2.98 [a] | 898.93 ± 131.13 |
| | Incongruent | 95.92 ± 2.89 [b] | 817.17 ± 122.14 [c] | 177.91 ± 69.05 | 87.87 ± 2.65 [a] | 871.21 ± 113.82 |

**Table 2.1** Performance scores on the colour word Stroop, physical and number word Stroop tasks of 5, 10 and 20 minutes in duration for the congruent and incongruent groups. [a] ($p$<.05), Significant difference between congruent and incongruent groups for the same task duration. [b] ($p$<.05), Significant difference in the incongruent group between 20 and 5 minutes. [c] ($p$<.001), Significant difference between the incongruent and congruent groups for all task durations. Data presented as M ± SD.

### 2.3.2 Colour word Stroop task performance

Separate 2 group (incongruent, congruent) by 3 time (5, 10, 20 minutes) ANCOVAs, with sex as a covariate, were performed on the percentage of correct responses and reaction time in the colour word Stroop task. The reaction time analysis revealed a main effect for condition, $F_{1,173} = 225.91$, $p<.001$, $\eta^2=.56$, with the congruent task (589.87 ± 84.16 ms) responding faster than the incongruent task (817.17 ± 122.14 ms). There was no main effect for time, $F_{2,173} = 2.82$, $p>.05$, $\eta^2=.03$, and no group-by-time interaction effect, $F_{2,173} = .59$, $p>.05$, $\eta^2=.01$. The percentage of correct responses analysis yielded no main effects for group, $F_{1,173} = 2.94$, $p>.05$, $\eta^2=.02$ ($M_{congruent} = 96.29$ ± 2.73 %, $M_{incongruent} = 95.56$ ± 2.83 %), time $F_{2,173} = .51$, $p>.05$, $\eta^2=.01$, and group-by-time, $F_{2,173} = 2.54$, $p>.05$, $\eta^2=.03$.

To gain more insight into the second aim of cognitive task performance as a function of time, the within-task cognitive task performance was analysed on the 20 minute length tasks in 5-minute time periods. This further analysis of the within-task reaction time of the 20 minute length tasks by a 2 group (incongruent, congruent) by 4 within-task time (0 to 5, 5 to 10, 10 to 15, 15 to 20 minute periods) ANOVA revealed a main effect for group, $F_{1,57} = 80.74$, $p<.001$, $\eta^2=.59$, and a group-by-within-task time interaction effect, $F_{3,55} = 4.17$, $p<.05$, $\eta^2=.19$, with the incongruent group recording faster reaction times of 879.68 ± 102.59 ms, 831.57 ± 143.28 ms, 774.71 ± 146.29 ms and 756.07 ± 150.64 ms in the 5-minute time periods as the task progressed. The incongruent group reaction times were faster than all the prior time periods with an exception in the final quarter, which was not faster than the preceding time period indicating that the performance improvements as the task progressed had plateaued. The incongruent group reaction time was slower than the congruent groups at all time quarters and the congruent groups reaction times were the same at each quarter throughout the task. A 2 group (incongruent, congruent) by 4 within-task time (0 to 5, 5 to 10, 10 to 15, 15 to 20 minutes) ANOVA on number of correct responses on the 20 minute tasks revealed a main effect for within-task time, $F_{3,55} = 5.45$, $p<.001$, $\eta^2=.26$, with the percentage of correct responses decreasing in the first 2 quarters from 96.35 ± 2.75 % to 95.63 ± 3.85 % before increasing slightly to 95.67 ± 3.25 % in the third quarter and then decreasing to 95.83 ± 3.17 % in the final quarter. No group differences were found, $F_{1,57} = .83$, $p>.05$, $\eta^2=.01$, in the percentage of correct responses given within the 5-minute time periods of the 20-minute tasks.

### 2.3.3 Number word Stroop task performance

Separate 2 group (incongruent, congruent) by 3 time (5, 10, 20 minutes) ANCOVAs, with sex as a covariate, were performed on the percentage of correct responses and reaction times for the number word Stroop task. Results for the percentage of correct responses yielded a main effect for group, $F_{1,173} = 90.72$, $p<.05$, $\eta^2=.06$, with the congruent group ($M$ = 86.61 ± 3.36 %) less accurate than the incongruent group ($M$ = 88.01 ± 2.62 %). There was no group-by-time interaction effect, $F_{2,173} = 1.07$, $p>.05$, $\eta^2=.01$, however there were differences in tasks of 10 and 20 minutes in length. No group differences, $F_{1,173} = 1.48$, $p>.05$, $\eta^2=.01$, were found in reaction times with the congruent group reacting in 884.21 ± 131.09 ms and the incongruent group in 863.46 ± 105.40 ms. There were also no group-by-time interaction effects. $F_{2,172} = .25$, $p>.05$, $\eta^2=.00$.

### 2.3.4 Ratings

#### 2.3.4.1 Fatigue and exertion

A series of 2 group (incongruent, congruent) by 3 time (5, 10, 20 minutes) ANCOVAs, with sex as a covariate, were performed on ratings of general fatigue at baseline and following the colour word and number word Stroop tasks (Table 2.2). At baseline, analysis revealed no group, $F_{1,173} = .03$, $p>0.5$, $\eta^2=.00$, or time, $F_{2,173} = .19$, $p>.05$, $\eta^2=.00$, differences in general fatigue. For the colour word Stroop task, the analysis revealed a main effect for time, $F_{2,173} = 13.25$, $p<.001$, $\eta^2=.13$ ($M_{5\text{-minute}} = 2.26 \pm 0.85 < M_{10\text{-minute}} = 2.79 \pm 0.95 < M_{20\text{-minute}} = 3.08 \pm 0.87$), and a group-by-time interaction effect, $F_{2,173} = 4.62$, $p<.05$, $\eta^2=.05$. General fatigue was greater for the 10-minute congruent group than the 10-minute incongruent group. Analysis of fatigue following the number word Stroop task revealed a group-by-time interaction effect, $F_{2,173} = 3.36$, $p<.05$, $\eta^2=.04$, with higher ratings reported in the congruent group for tasks of 10 and 20 minutes in length.

| | | Baseline | Word Stroop Task | Number Stroop Task |
|---|---|---|---|---|
| Duration | Condition | POMS fatigue (1-5) | POMS fatigue (1-5) | POMS fatigue (1-5) |
| 5 | Congruent | 1.95 ± 1.01 | 2.04 ± 0.77 [a] | 2.37 ± 0.75 [d] |
| | Incongruent | 2.10 ± 0.79 | 2.48 ± 0.87 [c] | 2.88 ± 0.92 |
| 10 | Congruent | 2.16 ± 0.83 | 3.05 ± 0.95 [a, b] | 2.95 ± 0.86 [d] |
| | Incongruent | 2.10 ± 0.83 | 2.53 ± 0.88 [c, b] | 2.63 ± 0.95 |
| 20 | Congruent | 2.11± 1.17 | 3.17 ± 0.88 [a] | 3.16 ± 0.99 [d] |
| | Incongruent | 2.1 ± 1.01 | 2.98 ± 0.86 [c] | 2.89 ± 0.99 |

**Table 2.2** General fatigue ratings following the colour word Stroop and number word Stroop tasks of 5, 10 and 20 minutes in duration for the congruent and incongruent groups. [a] (*p*<.001), Significant difference between the 5 minute congruent group 10 and 20 minute tasks. [b] (*p*<.05), Significant difference between the congruent and incongruent group for tasks of 10 minutes in duration. [c] (*p*<.05), Significant difference in the incongruent group between tasks 5 and 20 and 10 and 20 minutes in duration. [d] (*p*<.05), Significant difference between the 5 minute congruent group 10 and 20 minute tasks. Data presented as M ± SD.

A series of 2 group (incongruent, congruent) by 3 time (5, 10, 20 minutes) ANCOVAs, with sex as a covariate, were performed on ratings of MF at baseline and following the colour word and number word Stroop tasks (Table 2.3). At baseline, analysis revealed no group, $F_{1,173}$ = 1.04, $p$>0.5, $\eta^2$=.01, or time, $F_{2,173}$ = .89, $p$>.05, $\eta^2$=.10, differences in ratings of MF. For the colour word Stroop task, the analysis revealed a main effect for time, $F_{2,173}$ = 21.01, $p$<.001, $\eta^2$=.20 ($M_{5\text{-minute}}$ = 3.00 ± 1.95 < $M_{10\text{-minute}}$ = 4.83 ± 2.19 < $M_{20\text{-minute}}$ = 5.02 ± 2.05), and a group-by-time interaction effect, $F_{2,173}$ = 5.48, $p$<.05, $\eta^2$=.06. Similarly, to the general fatigue ratings, MF was greater for the 10-minute congruent group than the 10-minute incongruent group. Analysis of MF following the number word Stroop task revealed no group, $F_{1,173}$ = 1.79, $p$>0.5, $\eta^2$=.02, or time, $F_{2,173}$ = 1.74, $p$>.05, $\eta^2$=.10, differences in ratings of MF.

| | | Baseline | Word Stroop Task | Number Stroop Task |
|---|---|---|---|---|
| Duration | Condition | MF (CR10) | MF (CR10) | MF (CR10) |
| 5 | Congruent | 1.43 ± 1.77 | 2.59 ± 1.98 [a] | 3.85 ± 1.99 [d] |
| | Incongruent | 1.970 ± 1.85 | 3.41 ± 1.94 [c] | 4.46 ± 2.67 |
| 10 | Congruent | 2.31 ± 1.76 | 5.6 ± 2.00 [a, b] | 5.28 ± 2.06 [b,d] |
| | Incongruent | 1.87 ± 1.73 | 4.07 ± 2.12 [c, b] | 3.89 ± 2.28 [b] |
| 20 | Congruent | 2.15 ± 2.55 | 5.33 ± 2.33 [a] | 5.23 ± 2.77 [d] |
| | Incongruent | 2.26 ± 1.77 | 5.07 ± 1.76 [c] | 4.58 ± 2.07 |

**Table 2.3** Mental fatigue (CR10) ratings following the colour word Stroop and number word Stroop tasks of 5, 10 and 20 minutes in duration for the congruent and incongruent groups. [a] ($p$<.001), Significant difference between the 5 minute congruent group 10 and 20 minute tasks. [b] ($p$<.05), Significant difference between the congruent and incongruent group for tasks of 10 minutes in duration. [c] ($p$<.05), Significant difference in the incongruent group between tasks 5 and 20 and 10 and 20 minutes in duration. [d] ($p$<.05), Significant difference between the 5 minute congruent group 10 and 20 minute tasks. Data presented as M ± SD.

A pair of 2 group (incongruent, congruent) by 3 time (5, 10, 20 minutes) ANCOVAs, with sex included as a covariate, were performed on ratings of mental exertion following the colour word Stroop and number word Stroop tasks. Results for the colour word Stroop task revealed a time main effect, $F_{2,173}$ = 9.07, $p$<.001, $\eta^2$=.95, with ratings of 4.07 ± 2.19, 5.54 ± 2.24 and 5.26 ± 1.98 in the 5, 10 and 20-minute tasks respectively. Importantly, there were no group differences in mental exertion following the cognitive tasks.

A 2 group (incongruent, congruent) ANCOVA, with sex as a covariate, on RPE following the physical task revealed no group effect, with ratings of 2.59 ± 1.78 in the congruent group and 2.24 ± 1.37 in the incongruent group.

#### 2.3.4.2 Interest and enjoyment

A 2 group (incongruent, congruent) by 3 task (colour word Stroop, handgrip, number word Stroop) ANCOVA (covariate = sex) on the ratings of task interest and enjoyment revealed a main effect for task, $F_{2,176} = 6.78$, $p<.001$, $\eta^2=.07$, with ratings higher in the handgrip task ($M = 3.76 \pm 1.03$ ) than the colour word Stroop ($M = 3.24 \pm 1.07$) and number word Stroop task ($M = 3.34 \pm 0.96$ ). Neither the group main effect, $F_{1,177} = .66$, $p>.05$, $\eta^2=.00$, nor the group-by-task interaction effect, $F_{2,176} = 1.38$, $p>.05$, $\eta^2=.02$, were significant.

## 2.4 Discussion

This is the first known study to employ a triple task paradigm to investigate the time on task ego depletion effect of a cognitive response inhibition task on submaximal isometric handgrip endurance performance and a novel cognitive response inhibition task. The study had three specific aims. The first aim was to investigate the dose-response relationship of the duration of a cognitive response inhibition task on subsequent muscular endurance performance. The second aim was to investigate performance on a cognitive response inhibition task as a function of task duration. The third aim was to investigate the effects of the duration of a cognitive task on a subsequent novel cognitive task performance.

The first aim was to investigate the dose-response relationship concerning the effect of the duration of engagement in a cognitive response inhibition task on subsequent muscular endurance performance. We hypothesised that cognitive task duration would be inversely related to subsequent muscular endurance, but this was not supported by our findings. Physical performance was independent of response inhibition following cognitive tasks of 5 and 20 minutes duration, but a deterioration in physical performance did occur after 10 minutes. As presented in the introduction, previous research [20] has reported that hold time on a 50% MVC isometric handgrip task was reduced by 43% (14 seconds) after completing just 3 minutes and 40 seconds of an incongruent Stroop task compared to a congruent Stroop task. These findings helped form our hypothesis and we had expected to see response inhibition group differences following 5 minutes of the colour word Stroop test. However, the difference between these findings could be attributed to the 20% lower intensity of handgrip (30% relative to 50% MVC) in our study as higher levels of isometric muscle activation may require more self-control resources

[22]. We also did not take a baseline measure of isometric endurance performance, which would have increased peripheral physiological fatigue and impacted on performance in the outcome handgrip task. Additionally, the cognitive effort on a baseline handgrip task could have potentially resulted in more ego depletion and in combination with the additional reduction in any global self-control resource in the cognitive depletion task, impacted on the handgrip outcome task and reduced its duration. Following the cognitive tasks of 10 minutes we measured group differences in the physical task, which were 43% (56 seconds) lower in the incongruent group relative to the congruent group. This is consistent with previous findings [21] that reported the cognitive task needed to last at least 4 minutes to impair subsequent isometric handgrip task performance at 50%. The minimum 4 minute threshold appears to be in contradiction with the research groups own previous findings demonstrating that 3 minutes 40 seconds of the same response inhibition task was enough to impair physical performance at the same exercise intensity. However, in the study to determine the minimum threshold the cognitive task was conducted in 2-minute blocks separated by 30-second intervals for subjective ratings to be taken. It is possible that these brief periods of rest from response inhibition reduced the overall depletion of their self-control resource, which therefore required a longer task engagement to impair the subsequent physical performance. This study also did not investigate the effects of cognitive tasks over 10 minutes in duration so no comparison can be made with our results following 20 minutes of the cognitive task. The strength control model predicts that we should have observed larger decreases in performance following a longer engagement in the cognitive depletion task (as per our hypothesis). Maximal contractions also require high levels of self-control, motivation and mental effort to fully recruit the muscle motor units, yet evidence has established that performing

a prior cognitive task does not affect subsequent maximal muscular contractions [38–41]. This provides further evidence against the strength control model in explaining impaired exercise performance following brief cognitive tasks. The better explanation for our findings can be in the cognitive control model, 5 minutes of the incongruent Stroop task was not enough time to reallocate cognitive resources to manage the response inhibition demands and therefore had no impact on the following physical outcome task. When the task duration was doubled to 10 minutes a decrease in performance was observed. However, when this was doubled again to 20 minutes the performance detriments were diminished, possibly due to adaptation to the response inhibition task - which were investigated with the second aim.

The second aim was to investigate performance on the cognitive task as a function of task duration. We hypothesised that performance would decrease with time, which was not supported in either the congruent on incongruent groups. The incongruent groups did report an overall slower reaction time, which indicates the higher cognitive processing requirements to respond to the colour word stimuli. The percentage of correct responses was the same between the conditions indicating that the incongruent stimuli did not lower the accuracy of completing the task. To further investigate potential time on task learning effects and adaptation to the cognitive task, the 20-minute group’s within-task performance was analysed. We found that there was no time-on-task improvement in both reaction time and percentage of correct responses in the congruent group, however in the incongruent group there was time-related improvements in both reaction time and response accuracy. The reaction time increased each quarter relative to the previous quarter until the last 5 minutes of the task where it plateaued, potentially indicating that a ceiling limit had been reached, the participants had adapted to the response inhibition and as a result there is no impact on the subsequent physical performance relative to the congruent group. Consistent with our findings, cognitive improvements on the incongruent colour word Stroop test have been observed with decreased reaction time relative to baseline even when separated by a physical depletion task [22]. Additionally, learning effects on the colour word Stroop task have been demonstrated with a two-fold increased response accuracy following engagement in 144 trials relative to 48 trials [24], reaction times decreasing across a 6 block by 64 trial sequence with the largest improvements in the first 2 blocks [42], faster reaction times in a second block of a 3 block by 50 trial sequence [43] and overall the practice effects are well established [44]. These time on task performance improvements support the cognitive control theory, which predicts the allocation of attentional resources to the task at hand are likely to improve performance, rather than the strength control model which predicts that performance should decrease due to a reduction in the global self-control resource.

The third aim was to investigate the effects of the duration of a cognitive task on a subsequent novel cognitive task performance. The novel cognitive task was a number word Stroop test that required response inhibition which was also required in the incongruent groups on the initial colour word Stroop task. It was hypothesised that cognitive task duration would be negatively related to performance on the subsequent novel cognitive task. We found that the incongruent groups performed with faster reaction times, but with the same accuracy on the novel cognitive task regardless of the duration of the initial outcome task. This indicates that there must be a learning effect or adaptation to response inhibition that is developed in the initial cognitive task, which is not diminished by the short time period to complete the physical task and provide experimental ratings, and transfers to the novel cognitive task. Similarly, as with the within-task learning effects of the 20 minute cognitive incongruent Stroop task, this finding supports the cognitive control theory and opposes the strength control model.

We also recorded self-report measures of subjective ratings associated with each task. The participants in all groups had their task scores displayed (by university identity number) on a white board in the laboratory to increase motivation. Measures of interest and enjoyment were taken as an indirect measure of intrinsic motivation [45], with no group differences found and therefore indicating that participants were equally motivated to perform well on the tasks. We would have expected ratings of mental exertion, mental fatigue and general fatigue to be higher in the incongruent groups than the congruent, but where group differences were found the opposite occurred. Performance on the cognitive tasks was assessed on accuracy and response time. The participants in the congruent conditions would have attempted to complete the tasks as fast and as accurately as possible, which would have required a high level of focus and attention. This claim is supported by the same rating levels for cognitive task mental exertion between the incongruent and congruent groups. For tasks of 10 minutes in length the congruent group reported higher levels of mental fatigue than the incongruent condition. For tasks of 20 minutes duration no congruent group differences were found, and this could be due to the increase in within-task response time as the task progressed in the incongruent group, resulting in higher mental fatigue.

The reduced physical performance following the 10-minute cognitive task in the incongruent condition cannot be attributed to the development of mental fatigue through the engagement in the cognitive task. Additionally, if mental fatigue was the cause of the decreased physical performance, we would have expected to see an increase in the overall RPE rating for the physical tasks, however no group differences were reported. Studies typically use prolonged duration (90 minutes) of the AX continuous performance test (AX-CPT) cognitive task to induce a state of mental fatigue when investigating its impact on whole-body endurance exercise [27,46]. In these studies, performance across the AX-CPT task duration has varied with a 5% reduction in the accuracy of correct responses in the first 15 minutes relative to the last 15 minutes [27], and with no change from the first to last 3 minute time periods [46]. It is possible that a 3-minute time period might have been too short to measure performance differences due to task adaptation in the very early periods of the task, which may be masked when performance is measures over a longer time period (i.e. 15 minutes). We observed an increase in reaction time and number of correct responses in the first 15 minutes during 20 minutes of the incongruent colour word Stroop task, which plateaued in the last 5-minute time period indicating task adaptation and learning effects to response inhibition. If the task duration was increased past 20 minutes, it is possible that a state of mental fatigue would have developed and task performance deteriorated as observed on whole-body endurance exercise [28].

The strength control model has faced multiple challenges and criticisms as outlined in the introduction. These have been addressed by Baumeister who states that "despite challenges and updates, the limited energy model of self-regulation remains the best fit" in explaining self-regulation, ego depletion, and inhibition [47]. It was originally developed to explain the ego depletion effect in behavioural and lifestyle contexts rather than on exercise performance. However, when investigating the ego depletion effect on physical tasks the cognitive control model can better account for the adaptation to task demands, which improve performance and for a deterioration in performance when switching to a task in a different domain.

### 2.4.1 Limitations and future directions

This study has provided evidence in support of the cognitive control theory to explain the ego depletion effect, rather than the often cited strength control model, due to improved time on task cognitive performance and selective impact on subsequent outcome tasks. The findings should be interpreted considering several possible study limitations. No physiological measures were taken in this study, which would have provided further support and insight to explain how the performance was altered. For example, previous research has taken measures of muscle activation, cardiac response and cerebral blood flow to provide physiological evidence to explain the observed performance differences. Electromyography activity of the forearm muscles utilised in handgrip could have been recorded during the physical task as this has shown to be increased following brief response inhibition cognitive tasks [20]. Heart rate variability measures could have been recorded in both the physical and cognitive tasks to give an indication of autonomic nervous system changes in cardiac control as decreased vagal nerve activity and increased sympathetic nerve activity, have been interpreted in terms of increased mental load and increased task motivation and effort, respectively [48]. Cerebral hemodynamic measures on the pre-frontal cortex could have been taken as reduced oxygenated haemoglobin levels, suggestive of a higher mental effort, have been observed at exhaustion following a simultaneous submaximal handgrip and cognitive task relative to handgrip alone [49] and are investigated in later chapters of this thesis.

Subjective ratings of extrinsic motivation and attention could be taken to provide more information on the role of these processes on the ego depletion effect. However, too many questionnaires can increase the delay time between the tasks and diminish any ego depletion effects so should be used with caution. In the current study, RPE was only reported for the entire physical task, where the development of exertion across the task duration would have been of interest. However, when asking the participants to report RPE in the early phases of the physical task during pilot testing resulted in distraction and premature termination.

A third control condition group could be included that did not complete a computer-based cognitive task, but rather watched an emotionally neutral documentary for the same time periods. Engaging in the congruent Stroop task may have induced a mild state of mental fatigue and impaired the subsequent physical performance.

The triple task paradigm should be employed more often in the examination of the ego depletion effect, specifically when investigating it in the context of physical activity. It provides an opportunity to use tasks from both the same and different domains giving further insight into the effects of domain task switching on the ego depletion effect. Performance should also be monitored throughout the manipulation and outcome tasks so the ego depletion effect can be evaluated in relation to the development of mental fatigue, cognitive control theory as well as the strength control model.

### 2.4.2 Conclusion

The present study used a triple task (cognitive – physical – cognitive) design to investigate the ego depletion effect in the physical and cognitive domains. We have demonstrated that 10 minutes of engagement in a response inhibition task impairs subsequent isometric handgrip endurance performance at 30% MVC, but tasks of 5 and 20 minutes in length had no effect. Learning effects were observed in cognitive tasks of 20 minutes in length and completing a prior cognitive response inhibition task improved a novel cognitive response inhibition task completed several minutes later. All these results are best explained by the cognitive control theory.

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3

# Mental fatigue and isometric muscular endurance

## 3.1 Abstract

**Introduction:** Mental fatigue (MF) impairs whole-body endurance exercise and brief (<4 minutes) response inhibition tasks impairs isometric muscular endurance and is often attributed to the strength control model. The role of response inhibition on inducing MF and impairing isometric muscular contraction is not fully understood.

**Objectives:** To examine the effects of MF induced by a cognitive task without response inhibition on isometric muscular performance and to investigate any underlying physiological mechanisms.

**Methods:** 40 participants completed two bouts of cognitive tasks (2-back test or an emotionally neutral documentary) for 20 minutes followed by an isometric handgrip to exhaustion at 30% maximal voluntary contraction (MVC) in a randomized and counterbalanced order. Measures of electromyographic (EMG) forearm activity, pre-frontal cortex (PFC) cerebral haemodynamics (near infrared spectroscopy), and force were recorded. Measures of motivation, physical and mental exertion and MF were collected throughout.

**Results:** 20 minutes of the 2back test induced a state of MF as confirmed by self-report measures and reduced oxygenation in the PFC relative to watching the documentary. Isometric handgrip time to task failure at 30% MVC and EMG muscle activity in the extensor carpi radialis and flexor carpi ulnaris were the same in both conditions. There was an increased PFC blood flow during the physical task in the MF condition.

**Conclusion:** 20 minutes of a mentally demanding task, without response inhibition, induced a state of MF but did not impair subsequent isometric handgrip time to exhaustion at 30% MVC. The increased PFC blood flow during the physical task, when in a state of

MF, could be due to a compensatory rebound effect due to reduced tissue oxygenation during the prior 2-back task. These findings suggest response inhibition and/or task duration is an important component of a cognitive task in replicating the ego depletion effect on submaximal isometric handgrip.

## 3.2 Introduction

Mental fatigue is defined as a psychobiological state that can be caused by engaging in demanding cognitive activity for a prolonged period, and is often characterised by subjective feelings of tiredness and lack of energy [1]. The impact of mental fatigue on exercise performance and has been summarised in the review by Van Cutsem and colleagues [2], who concluded that its negative effects on subsequent submaximal whole-body endurance exercise are likely to be accounted for by elevated perceived exertion rather than cardiorespiratory and peripheral fatigue mechanisms.

Past experiments involving whole-body endurance exercise used a prolonged cognitive task (typically 30 to 90 minutes in duration) to induce a state of mental fatigue before asking participants to complete an endurance performance test. Briefer periods of cognitive task engagement (typically several minutes) have been used when investigating the impact of mental fatigue on isometric muscular endurance performance [3,4]. This research has established that performing a cognitive task to induce a state of mental fatigue does not affect subsequent maximal muscular contractions [5–8] but does impair submaximal contractions [3,9].

Bray and colleagues [3] reported that hold time on a 50% maximal voluntary contraction (MVC) isometric handgrip task was reduced after completing an incongruent Stroop task for several minutes and was associated with increased forearm electromyography (EMG) activity, indicative of a higher drive to activate the muscle motor units to maintain the required force. A later experiment by the same research group [9] examined the dose-response relationship between the incongruent Stroop task and isometric handgrip exercise at 50% MVC; reporting that the cognitive task needed to last at least 4 minutes to impair subsequent physical task performance. Bray and colleagues attribute the findings from their two experiments to the strength control model and the ego depletion effect.

The strength control model (also known as the strength-energy model) was originally proposed by Baumeister in 1994 and uses the analogy of a muscle to explain self-control [10]. As with a muscle, the more self-control is exerted the more fatigued it will become, depleting an individual's global self-control resource. This reduces the ability of an individual to regulate their actions impacting on other activities that also require the global self-control resource and is referred to as ego depletion. One element associated with ego depletion is an increase in mental fatigue [11], although it is difficult to establish if it is ego depletion or mental fatigue *per se* which is the cause of the decline in subsequent exercise performance. Additionally, the neurocognitive process underlying both effects are not well understood, although the prefrontal cortex (PFC) has been identified as being implicated in both effects [12].

The PFC consists of multiple interconnected areas that communicate with various subcortical structures in order to exert executive control, such as response inhibition, working memory and the facilitation of goal directed behaviour [13]. It has been suggested that during exercise the PFC interprets physiological information in combination with psychological factors, such as arousal and motivation, to facilitate a top-down effect on motor unit recruitment [14]. Additionally, activation of the PFC has been associated with working memory tasks [12], and specifically with the 2-back test [15].

The research described above that investigates the impact of ego depletion and mental fatigue on subsequent exercise performance has used a mentally demanding cognitive task prior to the physical performance task that required executive response inhibition processes, making it difficult to distinguish between these phenomena. Response inhibition is defined as “the ability to suppress behaviours that are inappropriate, unsafe, or no longer required” [16], which is a fundamental aspect of self-control. For optimal exercise performance, response inhibition is required to maintain high levels of exertion in the presence of fatigue, where a person’s natural response will be either to slow down or disengage from the task at hand. The present study was designed to separate the ego depletion effect from mental fatigue by using a cognitive task that does not require response inhibition to introduce a state of mental fatigue and had two specific aims.

The first aim investigated if engagement in a mentally demanding task without response inhibition induces mental fatigue and impairs subsequent isometric muscular endurance. We hypothesised that 20 minutes of engagement in a cognitive task without response inhibition will raise ratings of mental fatigue and impair subsequent isometric muscular endurance performance. The second aim examined the underlying physiological mechanisms via prefrontal cortex activation and muscle activity. We hypothesised that 20 minutes of engagement in a cognitive task without response inhibition will increase muscle activity and decrease PFC oxygenation during a subsequent isometric handgrip task to exhaustion.

## 3.3 Methods

### 3.3.1 Participants

The participants were 40 (17 females, 23 males) healthy undergraduate volunteers aged 25.00 ± 5.71 (Mean ± SD) years old. They were requested to abstain from vigorous exercise, the consumption of alcohol, and to obtain a regular night's sleep of approximately seven hours in the preceding 24-hour period. In the immediate hours beforehand, they were requested to refrain from eating (one hour) and consuming caffeine (three hours). Ethical approval for the experiment was obtained from the University of Birmingham Research Ethics committee. All participants provided written informed consent prior to study entry in accordance with the principles of the Declaration of Helsinki.

### 3.3.2 Experimental procedure

The participants attended the laboratory on one occasion, lasting for approximately one hour. Following an initial briefing the participants were fitted with electrodes for physiological measurements (see section 3.3.3) and completed a preliminary test to obtain their maximal voluntary contraction (MVC) grip force (see section 3.3.4). All participants were requested to remain seated on a stool throughout the experiment in front of a flat screen computer monitor positioned at eye level approximately 1 meter away. The participants were randomly allocated, by chance procedure, on order of engagement of the cognitive or control task (see section 3.3.5) with each followed by the physical task (see section 3.3.6). The cognitive task order was counter balanced, and the experimental protocol is shown in Figure 3.1. To increase participant motivation to perform to the best of their ability, a £20 retail voucher was offered for the best overall performance in all tasks. Before and after each task participants self-reported various psychological states related to each task (see section 3.3.7). Upon completion of the experiment participants had the electrodes removed and were thanked for their time.

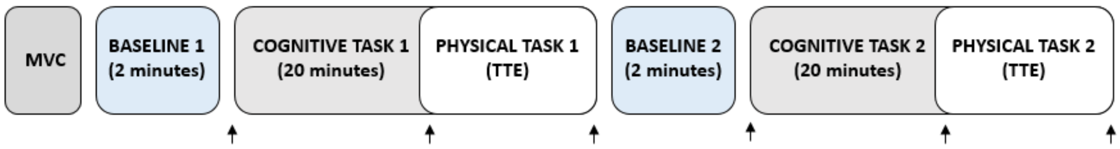


**Figure 3.1** Experimental Protocol. (Arrows indicate ratings questionnaires, TTE: Time to exhaustion)

### 3.3.3 Physiological measures

All physiological data were acquired via a Power 1401 (Cambridge Electric Design Limited, UK) multi-channel digital-to-analogue convertor (16-bit resolution at a sampling rate of 2.5 kHz) and the output continuously recorded on a computer using Spike 2 software (version 6.06).

#### 3.3.3.1 Prefrontal cortical haemodynamics

Prefrontal cortical haemodynamics were assessed using near infra-red spectroscopy (NIRS; NIRO-200NX, Hamamatsu Photonics KK, Japan). The NIRO-200 device measures changes in chromophore concentrations of oxyhaemoglobin and deoxyhaemoglobin ($\Delta O_2Hb$ and ΔHHb) via the modified Beer-Lambert law, and provides depth-resolved measures of tissue $O_2$ saturation [total oxygenation index (TOI)] and tissue haemoglobin (Hb) content (i.e., relative value of the total haemoglobin normalized to the initial value, nTHI) using the spatially resolved spectroscopy (SRS) method. The SRS-derived NIRS parameters limit contamination from superficial tissue via depth-resolved algorithmic methods, providing an index of targeted local tissue saturation (TOI) and perfusion (nTHI), see Davies et al. [17] for a recent review. Probes were enclosed in light-shielding rubber housing that maintained emitter-to-detector optode spacing (4 cm), positioned over the right pre-frontal electrode site (Fp2 in 10-20 system) and secured to the head with the manufactures bespoke double sided adhesive sticker. A head band was placed over the participant's forehead to further minimise external light interference. Before each cognitive task participants were instructed to sit still, relax, clear their mind and look at a fixation cross for 2 minutes to collect baseline measures of cerebral haemodynamics. Measures of TOI, nTHI, $O_2Hb$ and HHb were averaged over 60 s for the cognitive tasks and for each quartile of the physical task time calculated relative to the last 30 s of the prior baseline. Data were lost from four participants due to poor signal integrity during the tasks; this is reflected in the reduced degrees of freedom in the reported statistical analyses.

#### 3.3.3.2 Muscle activity

The forearm muscles utilised in gripping, the extensor carpi radialis and flexor carpi ulnaris, were fitted with differential surface electrodes to measure electromyographic (EMG) muscle activity. They were positioned, alongside a reference electrode, longitudinally on the humerous at approximately 10 cm from the medial epicondyle and 8 cm distal to the lateral epicondyle, respectively [18]. Muscle activity was captured with a dual channel Bagnoli-2 EMG system (Delsys, USA). The root mean square (RMS) of the EMG signals were averaged over 30 s and normalised as a percentage of EMG during MVC.

### 3.3.4 Maximum voluntary contraction

Participants were instructed to squeeze a handgrip dynamometer as hard as possible for several seconds in order to obtain their MVC [18]. They were not aware that the MVC informed the subsequent physical tasks. Participants held a bespoke handgrip dynamometer [19] in their dominant hand, placed on their knee, with their arm flexed at approximately 100 degrees. Participants performed a maximal contraction of the handgrip dynomometer and the peak force was recorded. This was repeated three times, with each contraction separated by a 1-minute rest to allow for recovery; the largest peak force achieved was recorded as the MVC. If the second highest peak force was not within 5% of the highest, another contraction was required.

### 3.3.5 Cognitive tasks

#### 3.3.5.1 2-back test

Participants completed 20 minutes of the 2-back test [20], which requires sustained attention and working memory but does not involve response inhibition [21]. Participants were shown a continuous series of random consonants, in which they were required to indicate if the current letter displayed was the same as the one presented two letters earlier. The letters were displayed once every two seconds for half a second in the centre of the monitor in a black 36-point Calibri font on a grey background. Participants used a standard UK computer keyboard with their non-dominant hand to press the number 1 if the current letter displayed was the same as the letter two prior and the number 2 if it was different, with performance determined by the percentage of correct responses. Prior to the test, participants completed a brief familiarisation of one minute in length and given written and verbal instructions (as shown in Figure 3.2). The 2-back test was generated with E-Studio (version 2.0.1.97, Psychology Software Tools, Inc., USA).

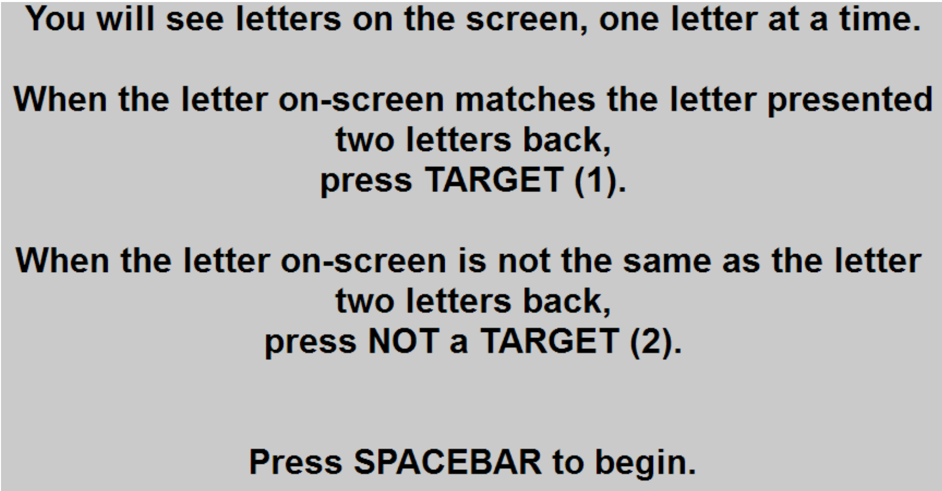


**Figure 3.2** 2-back cognitive task instructions

#### 3.3.5.2 Control task: emotionally neutral documentary

The control group watched the first 20 minutes of the documentary film "World Class trains – the American Orient Express" (Pegasus-Eagle Rock Entertainment, 2004), which has been shown to be emotionally neutral and maintains a stable physiological response in the viewer [22]. Before commencement of the video the experimenter described the video to the participant for a period of approximately one minute. This was to match the familiarisation and instruction time of the cognitive task and to maintain the same overall time before the subsequent physical task.

### 3.3.6 Physical task

The physical task required participants to maintain an isometric hold of the handgrip dynamometer with their dominant hand at 30% of their MVC for as long as possible. Visual feedback was given to participants via a single 40 mm wide-by-55 mm high dual-colour (green, red) 7-segment light emitting diode panel, which indicated the percent of their MVC, above or below the 30% threshold, their current grip force represented. Green numbers indicated a force equal to, or greater, than 30% MVC, whereas red numbers indicated a force less than 30% MVC. Participants were instructed to maintain a grip force that ensured a low green number for as long as possible. Task performance was determined by the duration of the isometric hold and was measured from task onset to the point when grip force fell below 30% MVC for more than two seconds. The standard deviation of the average force held for each quarter of the overall duration was analysed to indicate motor control stability.

### 3.3.7 Psychological state measures

#### 3.3.7.1 Motivation

Success motivation [23] was measured prior to each physical and cognitive task using a 5-point scale with anchors of "0 = not at all" and "4 = extremely"; example items included "I will be disappointed if I fail to do well on this task" and "I am eager to do well".

#### 3.3.7.2 Fatigue and exertion

The cognitive task was rated immediately following completion for mental exertion (ME) and mental fatigue (MF) on two 10-point category ratio (CR-10) scales. The scale for ME was anchored at each end of the scale with the descriptors "nothing at all" and "maximal mental exertion", while the MF scale was anchored with the descriptors "nothing at all" and "totally exhausted". Participants were reminded at each rating that these scales related to mental tiredness and exertion and not to physical sensations. In addition, ratings from the profile of mood states (POMS) subscale for fatigue were given on a 5-point Likert scale following the intervention and physical task

[24]. The constructs of exhausted, sleepy, tired and worn-out were rated and anchored with the descriptors "not at all" and "extremely". Ratings of perceived exertion (RPE) were given verbally immediately upon failure on the physical task on a 10-point CR-10 scale [25], anchored with the descriptors "nothing at all" and "maximal". The standard instructions for the scale were read to the participants prior to each physical task.

### 3.3.8 Statistical analysis

Statistical analysis was carried out using SPSS 24 software (SPSS: An IBM Company, Chicago, IL, United States). Statistical significance was set at $p<.05$. All data values were expressed as mean ± standard deviation of the mean (M ± SD) unless otherwise stated. The multivariate solution to ANOVAs has been reported. Partial eta-squared ($\eta_p^2$) was reported as the effect size, with values of 0.02, 0.13 and 0.26 indicating small, medium and large effects, respectively [26].

### 3.4 Results

### 3.4.1 Performance

The average endurance time following the control task was 178.40 ± 52.64 seconds and 181.46 ± 52.96 seconds following the 2-back task. These times were compared with a 2 task (cognitive, control) ANOVA, which revealed no difference, $F_{1, 39} = .15$, $p$=.71, $\eta^2$=.00, in hold times when the isometric handgrip endurance task was completed following the two different cognitive tasks. The standard deviation of the average percent of MVC maintained was analysed with a 2 task (2-back, control) by 4 quartile (1, 2, 3, 4) ANOVA, which revealed a main effect for quartile, $F_{3,37} = 165.25$, $p<.001$, $\eta^2$=.93, and no task differences. The average standard deviation of the mean percentage MVC maintained changed from 4.76 ± 0.05 %, 1.24 ± 0.02 %, 1.41 ± 0.02 %, 2.53 ± 0.02 % from quartile one to quartile four following both cognitive tasks.

The average MVC of the dominant hand across all participants was 423.80 ± 119.30 N, and a 2-tailed independent sample t-test revealed there was no difference in MVC for participants when they were split into groups based upon the order in which they completed the cognitive tasks.

The average percentage of correct responses on the 2-back task time when the cognitive task was completed first was 93.93 ± 4.45 % and 94.71 ± 3.58 % when the control task was completed first. These performance scores were compared with a one way ANOVA on task order (cognitive-control, control-cognitive), which revealed no difference, $F_{1, 39} = .38$, $p$=.54, $\eta^2$=.01, when the 2-back task was completed following the two bouts of isometric handgrip exercise to exhaustion compared to one.

### 3.4.2 Psychological task ratings

The average baseline POMS fatigue was rated as 1.98 ± 0.80 and MF was rated as 2.08 ± 1.53 across all participants. A series of individual one way ANOVAs on task (cognitive, control) were performed on the ratings of MF, fatigue, and ME on the cognitive task and motivation and RPE during the subsequent physical task. These tests revealed a cognitive task main effect for fatigue, $F_{1, 39} = 5.54$, $p<.05$, $\eta^2=.12$, and a task main effect for MF, $F_{1, 39} = 48.35$, $p<.001$, $\eta^2=.55$, which increased to 2.40 ± 0.93 and to 2.34 ± 1.57 following the control task and to 2.76 ± 0.83 and to 4.48 ± 1.92 cognitive tasks respectively. Results for ME on the cognitive task revealed a task main effect, $F_{1, 39} = 91.20$, $p<.001$, $\eta^2=.70$, with ratings of 1.63 ± 1.68 for the control task and 5.96 ± 2.23 for the cognitive task. No difference, $F_{1, 39} = .13$, $p=.91$, $\eta^2=.00$, was found in motivation to perform well on the subsequent physical task, with ratings of 2.97 ± 0.86 following the control and 2.96 ± 0.75 cognitive tasks. The RPE during the two physical tasks was similar, $F_{1, 39} = 2.47$, $p=.12$, $\eta^2=.06$, following the cognitive and control tasks with ratings of 6.42 ± 2.32 and 6.88 ± 2.15 respectively.

### 3.4.3 Physiological measures

#### 3.4.3.1 Cognitive task

A series of 2 task (2-back, control) by 20 time (20 one-minute periods) ANOVAs were performed on the FP2 prefrontal cortical haemodynamic responses of TOI, nTHI, $O_2Hb$ and HHb (Figure 3.3) during the cognitive tasks. This yielded a main effect for task, $F_{1,37} = 5.27$, $p<.05$, $\eta^2=.13$, for TOI. No differences in task or time were found for nTHI. Results for HHb revealed a main effect for time $F_{19,19} = 3.12$, $p<.05$, $\eta^2=.76$, and a task-by-time interaction, $F_{19,19} = 2.62$, $p<.05$, $\eta^2=.72$. Results for $O_2Hb$ revealed a main effect for task $F_{1,37}$ = 3.12, $p$<.05, $\eta^2$=.76, and a task-by-time interaction, $F_{19,19}$ = 5.68, $p$<.05, $\eta^2$=.13.

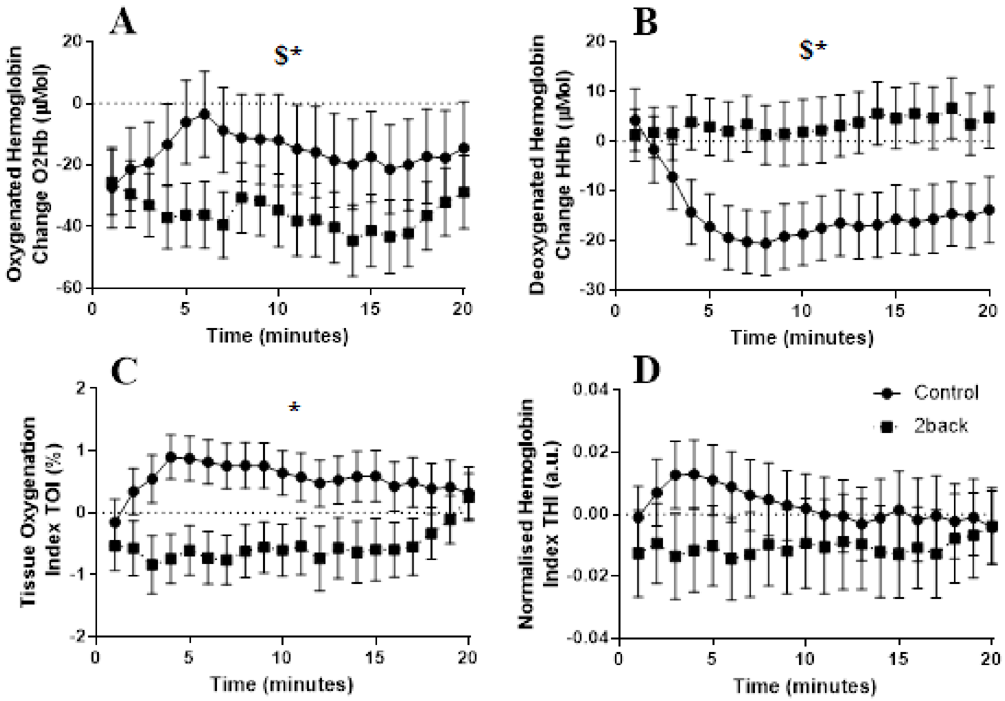


**Figure 3.3** PFC activation (FP2) for $O_2Hb$ (A), HHb (B), TOI (C) and nTHI (D) during the cognitive task. # Significant main effect for task ($p$<.05). $ Significant main effect for time ($p$<.05). * Significant task-by-time interaction ($p$<.05).

### 3.4.3.2 Physical task

A series of 2 task (2-back, control) by 4 quartile (1, 2, 3, 4) ANOVAs were performed on the FP2 prefrontal cortical haemodynamic responses of TOI, nTHI, $O_2Hb$ and HHb (Figure 3.4) during the physical tasks. This yielded main effects for quartile, $F_{3,35}$ = 6.81, $p$=.001, $\eta^2$=.38, and a task-by-quartile interaction, $F_{3.33}$ = 5.25, $p$<.05, $\eta^2$=.32, for TOI , a main effect for quartile, $F_{3,34}$ = 11.33, $p$<.001, $\eta^2$=.50, for nTHI, a main effect for quartile, $F_{3,34}$ = 34.27, $p$<.001, $\eta^2$=.75, for $O_2Hb$, and a main effect for quartile, $F_{3,34}$ = 20.57, $p$<.001, $\eta^2$=.65, and a task-by-quartile interaction, $F_{3.34}$ = 7.28, $p$=.001, $\eta^2$=.39, for HHb.

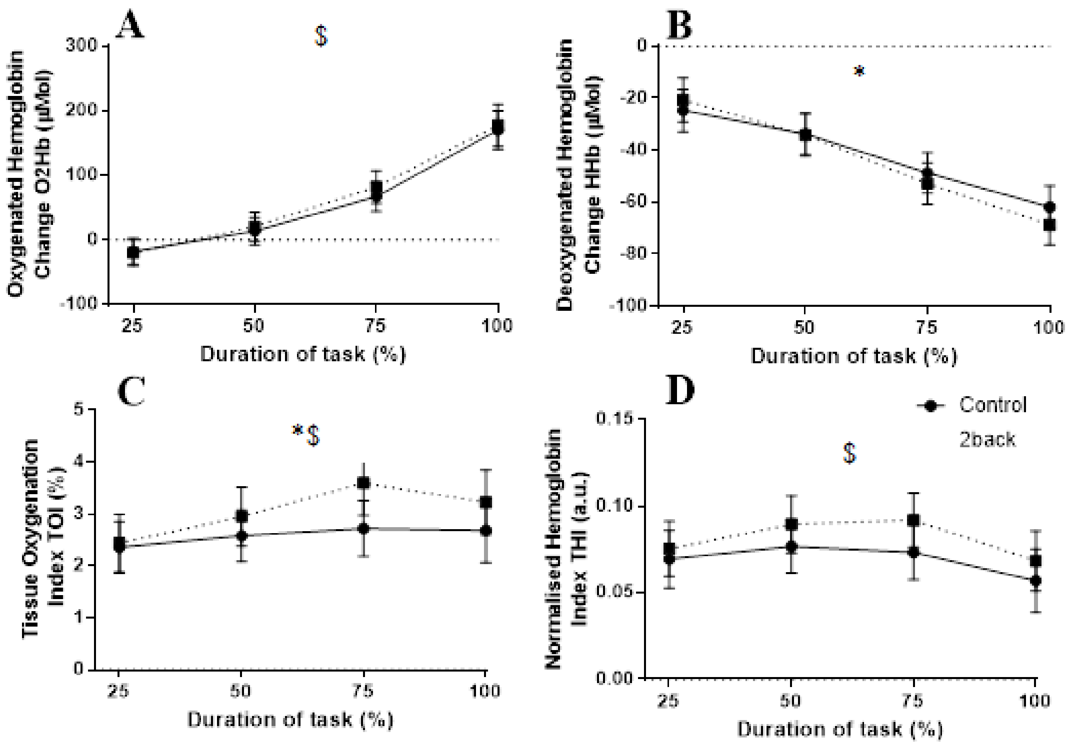


**Figure 3.4** PFC activation (FP2) for $O_2Hb$ (A), HHb (B), TOI (C) and nTHI (D) during the physical task. $ Significant main effect for time ($p$<.001). * Significant task-by-time interaction ($p$<.05).

The EMG muscle activity (figure 3.5) was analysed with a pair of 2 task (2-back, control) by 4 quartile (1, 2, 3, 4) ANOVAs, which yielded main effects for quartile in the extensor carpi radialis, $F_{3,36}$ = 15.20, $p$<.001, $\eta^2$=.56, and flexor carpi ulnaris, $F_{3,36}$ = 15.34, $p$<.001, $\eta^2$=.56, muscles. There were no task differences in muscle activity.

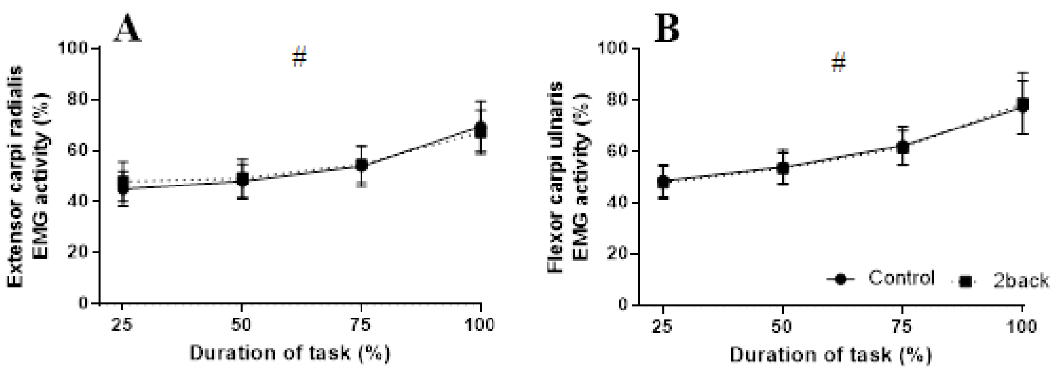


**Figure. 3.5** Effect of the physical task on the RMS EMG muscle activity as a percentage of activity during MVC in the extensor carpi radialis (A) and flexor carpi ulnaris (B). # ($p$<.05) Significant main effect of task duration. Data presented as M ± SEM.

### 3.5 Discussion

This study investigated the effects of a state of mental fatigue, induced by a cognitive task that did not require response inhibition, on submaximal isometric muscular endurance. The study had two specific aims. The first was to investigate if engagement in a mentally demanding task without response inhibition induces a state of mental fatigue and impairs subsequent isometric muscular endurance. The second study aim was to examine the underlying physiological mechanisms via PFC activation and muscle activity.

The first study aim was to investigate if engagement in a mentally demanding task without response inhibition induced a state of mental fatigue and impaired subsequent isometric muscular endurance. We hypothesised that 20 minutes of engagement in a cognitive task without response inhibition will raise ratings of mental fatigue and impair subsequent isometric muscular endurance performance. In contrast to our hypothesis, isometric muscular endurance at 30% MVC to exhaustion was not impaired as the time to exhaustion was the same in each condition. In support of the second part of this hypothesis we confirmed that 20 minutes of engagement in a 2-back task was enough time to induce a state of mental fatigue, as indicated by the higher subjective ratings of general fatigue and mental fatigue relative to the control task. Additionally, participants rated the mental exertion required to complete the 2-back task higher than the control task. In conjunction with the higher self-report rating of mental exertion during the 2-back task, the participants had a reduced oxygenation in their PFC, as indicated by a lower TOI, which we interpret as a greater physiological load associated with a higher mental effort relative to the control task.

Previous research by Bray and colleagues [3] demonstrated a reduction of 43% of isometric grip for time to exhaustion at 50% MVC, following three minutes and 40 seconds of an incongruent colour word Stroop task relative to a non-response-inhibition congruent version of the same task. The same research group conducted a similar follow up experiment [9], to examine the dose-response relationship between the length of engagement in an incongruent Stroop task and the capacity to conduct an isometric handgrip exercise at 50% MVC. As mentioned in the introduction of this chapter, they concluded that the cognitive response inhibition task needed to last at least four minutes to impair subsequent physical muscular endurance performance. However, as this later study did not investigate cognitive tasks longer than 10 minutes it is unknown if this effect, they reported is still present at 20 minutes.

The two main differences between these two studies and the present study was the intensity of isometric hold (30% vs. 50%) and the cognitive task type (response inhibition task versus non-response inhibition task). It is unlikely that the difference in handgrip intensity is the cause of the differences between these experiments, as both are submaximal and at or below half of the participants MVC. Indeed, muscle blood flow to the extensor carpi radialis longus muscle has been shown to be the same during three minutes of isometric handgrip at 30% and 45% MVC [27]. Bray and colleagues attribute the strength control model and ego depletion effect to explain the detrimental effect that mental fatigue has on subsequent physical performance. Given we observed no such effect here, it could be the specific task requirement of response inhibition which is required to impede subsequent physical performance. We specifically used the 2-back task so we could investigate if a state of mental fatigue, induced without response inhibition, would impair submaximal muscular endurance performance. It is possible that we did not measure a performance detriment as the cognitive task used does not require response inhibition. However, in chapter two of this thesis, data were presented demonstrating that 20 minutes of engagement in a cognitive task with response inhibition did not impair subsequent isometric handgrip performance at 30% MVC, which is consistent with the current findings. It is worth noting that a task of 10 minutes did impair subsequent performance.

Additionally, if the strength control model can account for the ego depletion effect then we would have expected to see a decline in cognitive task performance following the physical handgrip task, as this activity requires a high level of self-control [4]. To address this, we compared cognitive task results between the conditions when it was completed second and immediately after fatiguing handgrip exercise to exhaustion. However, we did not confirm this prediction based on the strength control model. Specifically, analysis of the standard deviation of the average force held as the task progressed revealed no differences between the conditions indicating that motor control was not impaired. The high standard deviation in the first quarter is likely to represent adjustment to the target force and task demands, and the elevated variation in the final quarter an increased lack of control to maintain the target force in the presence of increased fatigue. Taking the lack of physical performance detriment, the cognitive task results and motor control performance being the same in both conditions, indicates a lack of the ego depletion effect. This could be due to a lack of response inhibition processing required in the 2-back test.

The state of mental fatigue induced by the 2-back test in the current study was comparable (4.48 to 5.07) to the incongruent colour word Stroop task used in chapter two. However, in both situations the state of mental fatigue was not large enough to impair the subsequent isometric handgrip to exhaustion at 30% MVC. The shortest cognitive task duration to impair whole-body endurance exercise in the literature is 30 minutes [28], so it is possible that duration longer than 20 minutes would be needed to impair submaximal isometric performance. It was observed in the current study that the self-reported state of mental fatigue following the 20-minute cognitive task did not affect motivation to perform well on the subsequent physical task. Further, there was no difference in physical task performance and RPE was the same during both physical tasks. These findings contrast with the research on whole-body endurance exercise which have demonstrated that cognitive tasks of over 30 minutes in length induce a state of mental fatigue, raise RPE and reduce exercise performance [2]. As we did not want to distract the participants from concentrating on the physical task and maintaining the required force, we only asked the participants to indicate their RPE at the end of the task, which is at the point of fatigue and therefore it was not surprising that there was no difference in ratings. However, if it was possible to ask them to report RPE at regular intervals we may have observed an elevated RPE at the start of the task due to the induced state of mental fatigue

In sum, 20 minutes of a mentally demanding task was enough to induce a state of mental fatigue as confirmed by self-report ratings and a reduced oxygenation of the PFC but did not impair performance in a muscular endurance isometric handgrip task to exhaustion at 30% MVC.

The second aim was to examine the underlying physiological mechanisms via PFC activation and muscle activity. We hypothesised that 20 minutes of engagement in a cognitive task without response inhibition will increase muscle activity and decrease PFC oxygenation during a subsequent isometric handgrip task to exhaustion. In contrast to our hypothesis, muscle activity in both the extensor carpi radialis and flexor carpi ulnaris muscles was the same in both conditions. This conflicts with the previously discussed findings from Bray and colleagues [3], who reported increased forearm electromyography EMG activity in a time to exhaustion test at 50% MVC and in the vastus lateralis muscles during whole-body cycling exercise [7]. Bray and colleagues stated that this was likely due to depletion of self-regulation caused by the incongruent Stroop task. It is possible that we did not observe a raised EMG activity in the gripping muscles due to the lack of response inhibition in the 2-back task despite a state of mental fatigue.

As shown in Figure 3.4, we observed differences in the PFC haemodynamic responses that were measured during the physical task that followed the two different cognitive task conditions, although the hypothesised lower PFC oxygenation when in a state of mental fatigue was not observed. Instead, measured PFC tissue saturation (as indexed by TOI) was elevated following the 2-back task, which coincided with higher blood flow to that tissue. The increased PFC blood flow measured during the physical task following the 2-back task could be a result of an over compensatory rebound effect due to the decreased tissue saturation during the cognitive task (as shown in Figure 3.3C). Reduced oxygenated haemoglobin levels in the PFC, have been observed at exhaustion following a simultaneous submaximal handgrip and cognitive task relative to handgrip exercise alone [29]. Interestingly, we observed a drop in PFC blood flow (indexed by nTHI) and tissue oxygenation (i.e. TOI), at the point of fatigue in both task conditions. This finding is consistent with previous research demonstrating a reduced PFC oxygenation at the point of fatigue during whole-body endurance exercise [30,31]. The decline in PFC oxygenation could be a result of an increased mental effort to maintain the required force. If this is the case, then it would be expected that maintaining PFC oxygenation for as long as possible should improve physical task performance, as demonstrated in aerobically trained individuals relative to untrained [32]. The rebound in PFC blood flow measured following the 2-back task could have assisted in maintaining the effort to sustain the force during the physical task despite a state of mental fatigue, resulting in no differences in performance in each cognitive task condition.

In sum, in contrast to our hypothesis we did not measure an increase in EMG muscle activity or decline in PFC oxygenation following the 2-back task relative to control. Nevertheless, since we also observed no differences in performance between the two conditions, this lack of difference might be expected. Increases in EMG activity measured in previous research are probably due to the role of response inhibition used in the cognitive task, which is not required in the 2-back test. However, we cannot rule out other factors such as intensity of exercise and duration of the cognitive task. The engagement in the 2-back test for a period of 20 minutes was enough to induce a state of mental fatigue, and decrease PFC oxygenation, which may have resulted in an overcompensation effect (i.e. a hyperaemia response) during the physical task that maintained tissue saturation and therefore not impair performance.

### 3.5.1 Limitations

The present study has provided further insights into the role of mental fatigue and response inhibition on isometric endurance handgrip performance, but this experiment is not without its limitations. The study utilised a within-subject design and the tasks were completed on a single visit to the laboratory. It is possible that task learning effects and peripheral fatigue in the handgrip muscles could have influenced the results. However, as the tasks were completed in a counterbalanced permutation and there was a gap of at least 20 minutes between physical tasks, both possible confounding factors would have been reduced. To gain further insight into the oxygenation of the PFC it would have been beneficial to have had a response inhibition cognitive task condition.

### 3.5.2 Future directions

Further experimentation should be carried out to establish the role of cognitive task response inhibition on exercise performance and the duration of cognitive tasks to induce a state of mental fatigue and impair subsequent physical endurance performance. Chapter four of this thesis extends this work, further clarifying the role of response inhibition and task duration in the role of mental fatigue and exercise performance.

Many sports require a high level of cognitive processing, to maintain a high level of effort and optimal pacing strategy alongside tactical considerations and completion of complicated motor control movement patterns in order to perform to the best of one's ability. Athletes, from a large range of sports, often use mental imagery as a cognitive component of their warm-up routine for performance enhancement, arousal regulation, and affective and cognitive modification [33]. Future research should investigate the use of a brief cognitive task to be included as a component of a mental warm up as any compensatory cerebral blood flow could potentially improve performance. Care would have to be taken to ensure that a state of mental fatigue was not induced, which could impair the subsequent physical performance. Additionally, brief cognitive tasks involving response inhibition should also be avoided to avoid the ego depletion effect.

### 3.5.3 Conclusion

To conclude we have shown that 20 minutes of a mentally demanding task, without response inhibition, induced a state of mental fatigue but did not impair subsequent isometric handgrip time to exhaustion at 30% MVC. This could be due to the lack of response inhibition in the cognitive task, its duration, or a combination of both factors. There was an increased PFC blood flow during the physical task, which could be due to a compensatory rebound effect due to reduced tissue oxygenation during the prior 2-back cognitive task. Future research should investigate brief cognitive tasks as part of a mental warm up routine to potentially improve physical performance.

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4

# Mental fatigue and rhythmic muscular endurance

## 4.1 Abstract

**Introduction:** Mentally-fatiguing cognitive tasks can impair subsequent endurance performance. The effects of task duration and the importance of response inhibition during the cognitive task have yet to be established. Additionally, there is limited information available regarding the physiological and psychological indices of mental fatigue

**Objectives:** To compare the effects of a series of bouts of cognitive tasks with and without response inhibition on self-paced rhythmic handgrip exercise and physiological and psychological indices of mental fatigue.

**Methods:** Participants (n=90) were randomly assigned to one of three cognitive task groups (Stroop, 2-back, control) and completed four blocks of 10 minutes engagement in a cognitive task followed by five minutes of a physical handgrip task which required the generation of as much force as possible once a second for 300 s. Heart rate (HR), HR variability (HRV), electromyographic (EMG) forearm activity, and force were recorded throughout along with measures of motivation, physical and mental exertion and mental fatigue.

**Results:** The 2-back and Stroop participants had higher HR and lower HRV and reported greater fatigue, mental effort, and interest/enjoyment than the control group during the cognitive tasks. The control group produced more force than the 2-back in blocks 2, 3 and 4 and blocks 2 and 3 for the Stroop group. There were no differences in EMG forearm activity ($p<.05$).

**Conclusion:** Performing a cognitive task for 10 minutes induces a state of mental fatigue as confirmed by self-report ratings and HRV measures. 20 minutes of engagement in a

cognitive task impaired subsequent dynamic rhythmic muscular endurance performance independent of response inhibition. The duration of cognitive task engagement falls between the thresholds reported in the literature for isometric (a few minutes) and whole-body (half an hour) endurance exercise

## 4.2 Introduction

Mental fatigue, defined as a psychobiological state that can be caused by engaging in demanding cognitive activity for a prolonged period, is often characterised by subjective feelings of tiredness and lack of energy [1]. It has been associated with reduced accuracy [2], slower reaction time [2], and impaired workplace performance [3]. The underlying neural mechanisms have yet to be established [4]. Changes in neural activity associated with mental fatigue have been investigated in terms of cortical activity during the completion of tasks requiring a high level of cognitive processing [5]. Recently, multifactorial brain connectome approaches have been utilised, which employ multivariate functional connectivity analysis of neuroimaging to better understand the neural mechanisms underlying and identify the presence of mental fatigue [6]. The dual regulation system model of mental fatigue [4] proposes that a high cognitive demand activates both the mental facilitation and inhibition systems, and thereby causes mental fatigue. The mental facilitation system is an interconnecting neural circuit that connects the limbic system, basal ganglia, thalamus and frontal cortex. When motivation is high, the mental facilitation system is activated through increased dopaminergic drive, which increases effort and maintains cognitive task performance in the presence of a high mental demand, but over time can cause dysfunction and induce mental fatigue. The mental inhibition system comprises the insular cortex and posterior cingulate cortex, and activation can occur during any mentally demanding task, even those of low demand, and can impair cognitive task performance. In sum, mental fatigue is a common sensation which can result in multiple negative outcomes in daily life and there is little understanding as to the underlying neural mechanisms.

### 4.2.1 Assessment of mental fatigue

The peripheral physiological effects of mental fatigue have been assessed using changes in automatic nervous system activity, including heart rate variability (HRV) measured using time and frequency domain characteristics of the R-R interval of the electrocardiogram [7]. For instance, prolonged engagement (30 minutes) in the 2-back memory task was associated with increases in heart rate due to decreased vagal nerve activity and increased sympathetic nerve activity, which were interpreted in terms of increased mental load and increased task motivation and effort, respectively [8].

Performance on the psychomotor vigilance test (PVT) has been used to assess mental fatigue [9]. The PVT has been criticized as a method of assessing mental fatigue since it takes 10 minutes to complete and can itself cause mental fatigue [10]. Truncated versions have been designed, with the briefest version taking 3 minutes to complete, that can reliably detect mental fatigue [10]. Questionnaires and scales have been used extensively to measure self-reported mental fatigue [11]. Such ratings have detected mental fatigue during the PVT despite strong performance, presumably because of activation of the mental facilitation system. This raises the question of the practical suitability of the PVT in assessing mental fatigue. Finally, self-reported mental fatigue has been observed for up to an hour following a 45 minute response inhibition task [12]. Taking all the above aspects into consideration it appears that self-report measures and scales seem to be the most reliable and practical measures of mental fatigue.

### 4.2.2 Mental fatigue and exercise performance

The last decade has witnessed extensive research on the impact of mental fatigue on subsequent endurance exercise performance and is summarised in a recent systematic review by Van Cutsem et al. [13]. In these studies participants perform a cognitive task to induce a state of mental fatigue and then perform an endurance exercise test. The seminal study by Marcora and colleagues [1] induced a state of mental fatigue in participants using the 90-minute AX continuous performance (AX-CPT) test. The AX-CPT requires executive functions, such as attention, response inhibition, memory and error monitoring. In a subsequent submaximal cycling (80% peak power output) time to exhaustion (TTE) test, task disengagement occurred almost two minutes (15% of control task duration) earlier when in a state of mental fatigue. Importantly, this mental fatigue-related performance impairment occurred with no differences in heart rate (HR), stroke volume, cardiac output, mean arterial pressure, oxygen consumption, minute ventilation and blood lactate relative to a control condition. However, participants in the mental fatigue condition started the TTE at a higher perceived exertion (RPE) rating. RPE increased similarly in both conditions as a linear function of time, and, therefore, the maximal tolerable level was reached earlier in the mental fatigue condition, leading to earlier task disengagement compared to the control condition. The authors speculated that the elevated RPE was due to increased activity in the anterior cingulate cortex (ACC), which has been implicated in both cognitive and physical tasks [14], and ACC activity is positively correlated with RPE in both real and perceived exercise tasks [15,16].

MacMahon and colleagues [17] examined the effect of a 90-minute AX-CPT on a subsequent 3-km running time trial (TT). Running times were 2% slower in the mental fatigue condition compared to control, with no condition differences in RPE, HR, blood lactate, pacing, and attention. Another study [18] investigated the effect of a 30-minute Stroop task on a 5-km running TT to examine the role of response inhibition during the mentally-fatiguing cognitive task on subsequent exercise performance. Running times were 6% slower following the incongruent (inhibition) version compared to the congruent (control) version of the Stroop task. The two conditions produced the same mental fatigue, motivation, pacing and terminal RPE, whereas heart rate, mental demand, and RPE during the TT were greater after the incongruent Stroop compared to the congruent Stroop. These data provide some support for the argument that response inhibition during the cognitive task increased RPE and decreased performance in the subsequent bout of exercise. Taken together, these findings indicate that tasks requiring response inhibition can impair subsequent self-paced endurance exercise regardless of the state of mental fatigue. In sum, the evidence indicates that the negative effect of mental fatigue on subsequent submaximal whole-body endurance exercise is more likely to be accounted for by elevated RPE rather than cardiorespiratory and peripheral fatigue mechanisms [13,19,20] or pacing strategies [21].

Evidence has established that performing a cognitive task does not affect subsequent maximal muscular contractions [22–25] but does impair submaximal contractions [25-26]. Bray and colleagues [26] reported that hold time on a 50% maximal voluntary contraction (MVC) isometric handgrip task was reduced after completing a short (3:40 minutes) incongruent Stroop task (endurance = 32 seconds) compared to a congruent Stroop task (endurance = 46 seconds). The impaired performance was associated with increased forearm electromyography (EMG) activity, indicative of a higher drive to activate the muscle motor units to maintain the required force. A later experiment by the same research group [27] examined the dose-response relationship between the incongruent Stroop task and isometric handgrip exercise at 50% MVC: the cognitive task needed to last at least 4 minutes to impair subsequent physical task performance.

### 4.2.3 The present study

The evidence reviewed above establishes that a mentally-fatiguing cognitive task can impair exercise endurance. Nonetheless, there remain gaps in our understanding of the mental fatigue-endurance relationship. First, studies have yet to demonstrate the temporal effects of mental fatigue on subsequent exercise performance since previous studies have all induced mental fatigue using a single task period. Second, the importance of response inhibition during the cognitive task has yet to be established. The present study was designed to address these gaps by comparing the effects of a series of bouts of cognitive tasks with and without response inhibition on self-paced rhythmic handgrip exercise and indices of mental fatigue.

The study has three specific aims. The first study aim was to assess the effects of a cognitively demanding task (with and without response inhibition) on psychological and physiological indices of mental fatigue as a function of time. The second study aim was to investigate the effects of cognitive tasks on subsequent performance on a dynamic rhythmic muscular endurance task as a function of time. The third study aim was to investigate the effects of cognitive tasks on psychological and physiological measures during the endurance task as a function of time. Based on the literature described above we expected that ratings of mental fatigue would increase and measures of HRV would decrease as a function of time when performing a mentally demanding cognitive task with and without response inhibition. It was expected that a state of mental fatigue, induced using the cognitive task with response inhibition and the cognitive task without response inhibition, would reduce performance on a subsequent muscular endurance task by a similar amount. However, as no previous research has examined performance on a dynamic muscular endurance task it is difficult to specify the duration of prior cognitive task engagement required to impair performance. Finally, physical performance was hypothesised to occur with the same cardiac response measures and increased RPE and EMG muscle activity following mentally demanding cognitive tasks.

## 4.3 Methods

### 4.3.1 Participants

Participants were 90 (52 females, 38 males; aged 19.4 ± 1.3 years) healthy undergraduate students volunteers who received course credit for participation. They were asked to abstain from vigorous exercise and alcohol, and to have a regular night's sleep in the 24 hours before testing. They were also asked to refrain from eating (one hour) and consuming caffeine (three hours) before testing. Ethical approval for the study was obtained from the local Institutional Ethics Committee and participants provided written informed consent.

### 4.3.2 Experimental design and procedure

The study employed an experimental design with one between-participant factor (group: Stroop task, 2-back task, control task) and one within-participant factor (block: 1, 2, 3, 4). Each block consisted of 10 minutes engagement in a cognitive task followed by 5 minutes of a physical handgrip task. Participants attended one laboratory session. Following an initial briefing, participants were instrumented for physiological measurements (section 4.2.6). Participants were asked to remain seated on a stool throughout and face a computer monitor positioned at eye level 1 meter away. After obtaining the participant's maximal voluntary contraction (MVC) grip force (section 4.2.3), they were randomly allocated to one of three groups, which differed in terms of cognitive task (section 4.2.4). Each group completed four 10-minute blocks of the cognitive task followed by a 5-minute handgrip task (section 4.2.5). Participants provided ratings before and after each task (section 4.2.7). They received instruction and completed a 1-minute familiarisation of the cognitive task. To increase motivation to perform a £20 retail voucher was offered for the best overall task performance in each group. The experimental protocol is shown in Figure 4.1.

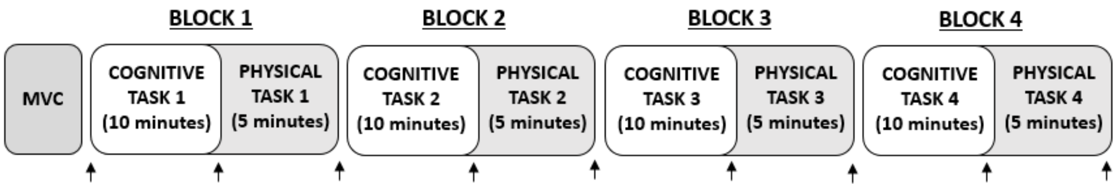


**Figure 4.1** Experimental Protocol. (Arrows indicate timing of ratings questionnaires)

### 4.3.3 Maximum voluntary contraction

Participants were instructed to squeeze a handgrip as hard as possible for several seconds in order to obtain their MVC [28]. They were not aware that the MVC informed the subsequent physical tasks. A bespoke handgrip dynamometer [29] was held in their dominant hand, placed on their knee, with their arm flexed at approximately 100 degrees. Participants performed a maximal contraction of the handgrip and the peak force was recorded. This was repeated three times with each contraction separated by a rest period of one minute to allow for recovery with the largest peak force achieved recorded as their MVC. If the second highest peak force was not within 5% of the highest another attempt was required.

### 4.3.4 Cognitive task groups

#### 4.3.4.1 2-back group: Cognitive task without response inhibition

The 2-back test [30] activates [31] the anterior cingulate cortex (ACC), involves working memory but does not involve response inhibition [32]. Participants were shown a continuous series of random consonants: they were required to indicate if the current letter displayed was the same as the one presented two letters earlier. The letters were displayed once every 2 s for 500 ms in the centre of the monitor. Participants used a keyboard with their non-dominant hand to press the number 1 key if the current letter displayed was the same as the letter two prior, and the number 2 key if it was different. Task performance was assessed by the percentage of correct responses.

#### 4.3.4.2 Stroop group: cognitive task with response inhibition

The incongruent Stroop colour-word test [33] activates the ACC, and involves working memory and response inhibition [34]. A series of five colour words (red, green, brown, yellow, blue) were individually displayed in capital letters once every 2 s in the centre of the monitor in a different font colour to the word meaning. Participants were instructed to verbally name the font colour of the word as quickly and accurately as possible. Performance was assessed by the percentage of correct answers by an experimenter sat behind the participant. If the participant failed to name the correct colour of the word whilst it was displayed, stutter, or self-correct, the response was deemed incorrect. Both the 2back and Stroop cognitive tasks were generated with E-Studio (version 2.0.1.97, Psychology Software Tools, Inc., USA).

#### 4.3.4.3 Control group: emotionally neutral documentary

The control group watched one of two documentary films from the same series (Pegasus-Eagle Rock Entertainment, 2004); “World Class trains – the American Orient Express” or the “World Class trains – the Venice Simplon Orient Express”. These films were selected as the latter has been shown to be emotionally neutral and to maintain a stable physiological response in the viewer [35], and they have been used as control tasks in similar experiments [1,25]. Participants watched the first minute of the documentary as task familiarisation to standardize the timeframe across groups.

### 4.3.5 Physical task

The physical task required participants to hold the bespoke handgrip dynamometer in the same position as during the MVC and to squeeze it with their dominant hand once a second (i.e. at 1 Hz), indicated by an audio metronome, for 5 minutes. A standardised script was read to participants before the task, at 150 s, and at 270 s, instructing them to “generate as much force as possible in the timeframe for a chance of winning a £20 voucher”. The task time was indicated to participants at 60, 120, 180, 240 and 295 s. Performance was determined by the average peak force as a percentage of MVC per second (force %MVC/s) over the 5 minute task. The force generated per minute as a percentage of total force accumulated over the task was calculated to characterize pacing strategy. A 1-minute familiarisation task with visual performance feedback was scheduled after the MVC task.

### 4.3.6 Physiological measures

All physiological data were acquired via a Power 1401 (Cambridge Electric Design Limited, UK) multi-channel analogue-to-digital convertor (16-bit resolution at a sampling rate of 2.5 kHz) and recorded on a computer running Spike 2 software (version 6.06).

#### 4.3.6.1 Cardiac responses

Electrocardiographic (ECG) activity was recorded using silver/silver chloride spot electrodes (Cleartrace, ConMed, USA) attached to the lower left rib, left clavicle and right clavicle connected to an amplifier (509 cardiac monitor, (Morgan, USA). HR and HRV were computed from the R-R intervals. The root mean square of the successive differences (rMSSD) and the standard deviation (SDNN) of the R-to-R wave interval were calculated as time domain surrogates of the high frequency (0.15 to 0.40 Hz) and lower (0.04 to 0.15 Hz) spectral band, respectively. These measures reflect changes in cardiac control via the parasympathetic and combined sympathetic and parasympathetic components, respectively [28].

#### 4.3.6.2 Muscle activity

The EMG activity of the forearm muscles used in gripping, the extensor carpi radialis and flexor carpi ulnaris, was measured using differential surface electrodes. They were positioned, alongside a reference electrode, longitudinally on the humorous at approximately 10 cm from the medial epicondyle and 8 cm distal to the lateral epicondyle, respectively [28]. Muscle activity was recorded using a Bagnoli-2 EMG system (Delsys, USA). The EMG signals were rectified, averaged over 30 s, and normalised as a percentage of EMG at MVC. Data were lost from seven participants due to poor EMG recordings during the handgrip task; this is reflected in the reduced degrees of freedom in the reported statistical analyses.

### 4.3.7 Psychological state measures

#### 4.3.7.1 Fatigue and exertion

The cognitive task was rated immediately following completion for mental exertion (ME) and mental fatigue (MF) on 10-point category ratio (CR-10) scales. The ME scale was anchored with the extreme descriptors “nothing at all” and “maximal mental exertion”. The MF scale was anchored with the extreme descriptors “nothing at all” and “totally exhausted”. Participants were reminded that these scales related to mental tiredness and exertion and not physical sensations. Following the intervention and physical task, items (exhausted, sleepy, tired, worn-out) from the fatigue subscale of the profile of mood states (POMS) were rated on a 5-point scale with anchors of 1 “not at all” and 5 “extremely” [36]. Ratings of perceived exertion (RPE) were given verbally during the physical tasks at 60, 120, 180, 240 and 295 s on a 10-point CR-10 scale [37], anchored with the descriptors “nothing at all” and “maximal”. A task average RPE was calculated from the five ratings. The standard instructions for the scale [38] were read to participants prior to each physical task.

#### 4.3.7.2 Interest and enjoyment

Task interest and enjoyment was measured using the interest/enjoyment subscale of the intrinsic motivation inventory [39]. Participants were presented with seven items (e.g., “I enjoyed doing this activity very much”, “I would describe this activity as very interesting”), and responded on a 7-point scale, with anchors of 1 “not true at all” and 7 “very true”.

### 4.3.8 Statistical analysis

Statistical analysis was carried out using SPSS 24 software (SPSS: An IBM Company, Chicago, IL, United States). Statistical significance was set at $p<.05$. All data values were expressed as mean ± standard deviation of the mean (M ± SD) unless otherwise stated. The multivariate solution to ANOVAs has been reported. Partial eta-squared ($\eta_p^2$) was reported as the effect size, with values of 0.02, 0.13 and 0.26 indicating small, medium and large effects, respectively [40]. Significant ANOVA effects were followed by least significant difference (LSD) post-hoc tests.

## 4.4 Results

### 4.4.1 Cognitive task – Performance

Cognitive task performance was analysed with a 2 group (2back, Stroop) by 4 block (1, 2, 3, 4) ANOVA revealing a main effect for group $F_{1,58} = 62.77$, $p<.001$, $\eta^2=.52$ and block $F_{3,56} = 6.43$, $p=.001$, $\eta^2=.26$; percentage of correct responses on the Stroop task from blocks 1 to 4 were 97.37 ± 2.86 %, 98.66 ± 1.66 %, 98.76 ± 1.42 % and 98.62 ± 1.50 and 85.70 ± 6.88 %, 87.37 ± 8.32 %, 88.82 ± 8.33 % and 89.32 ± 7.60 % on the 2back task.

### 4.4.2 Cognitive task - Psychological ratings

Ratings of post-cognitive task MF, ME, POMS fatigue, and interest/enjoyment are shown in Figure 4.2. Separate 3 group (Control, 2-back, Stroop) by 4 block (1, 2, 3, 4) ANOVAs revealed group effects for MF, $F_{2,87} = 22.31$, $p<.001$, $\eta^2=.34$, ME, $F_{2,87} = 61.25$, $p<.001$, $\eta^2=.59$, fatigue, $F_{2,87} = 3.75$, $p<.05$, $\eta^2=.08$, and interest/enjoyment, $F_{2,87} = 5.14$, $p<.05$, $\eta^2=.11$, as well as block effects for MF, $F_{3,85} = 29.07$, $p<.001$, $\eta^2=.51$, ME, $F_{3,85} = 9.60$, $p<.001$, $\eta^2=.25$, fatigue, $F_{2,85} = 25.48$, $p<.001$, $\eta^2=.47$, and interest/enjoyment, $F_{2,85} = 16.67$, $p<.001$, $\eta^2=.37$. Post-hoc comparisons confirmed that the 2-back and Stroop groups reported greater fatigue, mental effort, and interest/enjoyment than the control group. Ratings of fatigue and effort tended to increase monotonically from the first to the last block of cognitive tasks whilst ratings of and interest/enjoyment tended to increase. Finally, a 3 group (Control, 2-back, Stroop) ANOVA confirmed there were no group differences in pre-cognitive task (i.e., baseline) MF, $F_{2,87} = 1.84$, $p = .16$, $n_p^2 = .04$, $M = 2.10 \pm 1.50$, and POMS fatigue, $F_{2,87} = .82$, $p = .45$, $n_p^2 = .02$, $M = 1.90 \pm 0.80$.

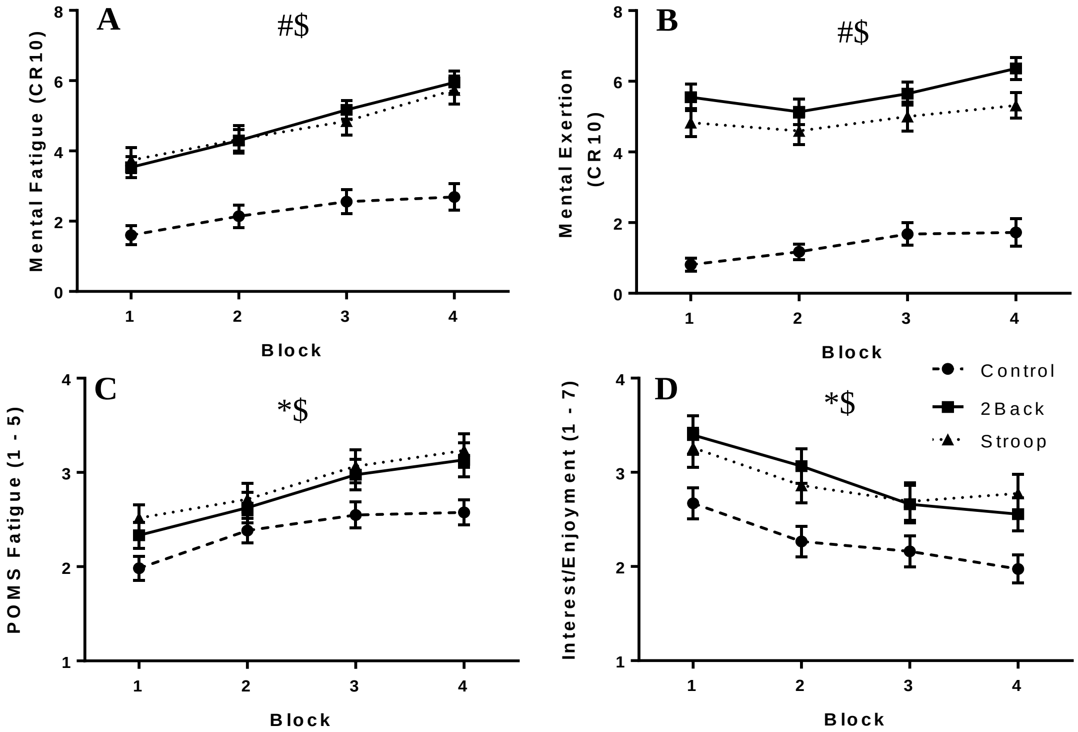


**Figure 4.2** Effect of the cognitive task on the psychological self-report ratings of mental fatigue (A), mental exertion (B), fatigue (C) and interest/enjoyment (D) over 4 repeated blocks. # (p<.001), * (p<.05), Significant main effect of group. $ (p<.001), Significant main effect of block. Data presented as M ± SEM.

### 4.4.3 Cognitive task - Physiological measures

The cardiac measures of HR and HRV (RMSSD, SDNN) during the cognitive tasks (Figure 4.3) were analysed with a series of 3 group (Control, 2-back, Stroop) by 4 block (1, 2, 3, 4) ANOVAs. These analyses yielded group effects for SDNN, $F_{2,87} = 3.90$, $p<.05$, $\eta^2=.08$, and RMSSD, $F_{2,87} = 8.41$, $p<.001$, $\eta^2=.16$, plus block effects for HR, $F_{3,85} = 33.20$, $p<.001$, $\eta^2=.54$, SDNN, $F_{3,85} = 21.75$, $p<.001$, $\eta^2=.43$, and RMSSD, $F_{3,85} = 9.17$, $p<.001$, $\eta^2=.25$. A group-by-block interaction effect was found for HR, $F_{3,86} = 3.40$, $p<.05$, $\eta^2=.11$. Post-hoc tests confirmed that the 2-back and Stroop groups exhibited higher HR and lower HRV than the control group (see Figure 2), while HR slowed and HRV rose from block 1 to 4.

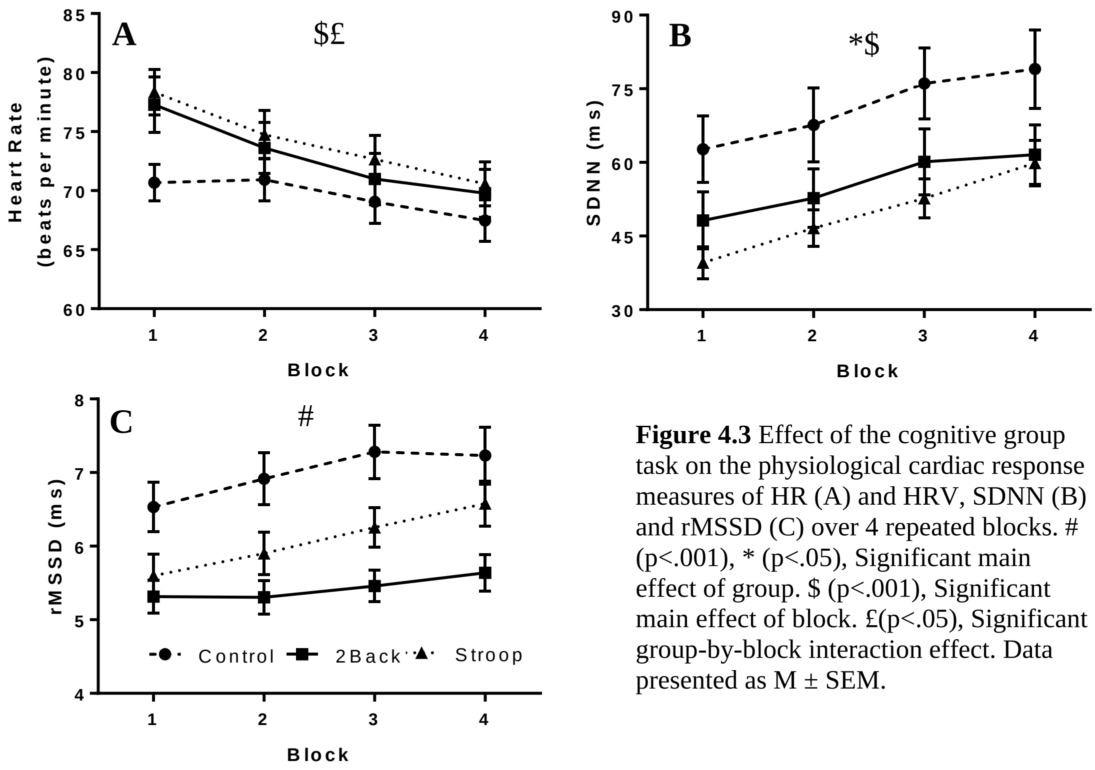


**Figure 4.3** Effect of the cognitive group task on the physiological cardiac response measures of HR (A) and HRV, SDNN (B) and rMSSD (C) over 4 repeated blocks. # (p<.001), * (p<.05), Significant main effect of group. $ (p<.001), Significant main effect of block. £(p<.05), Significant group-by-block interaction effect. Data presented as M ± SEM.

### 4.4.4 Physical task - Performance

A 3 group (Control, 2-back, Stroop) ANOVA confirmed that the maximum grip strength (i.e., MVC) of the groups did not differ, $F_{2,87}$ = 0.78, *p*=.46, $\eta^2$=.02; *M* = 395.82 ± 99.79 N. Physical task performance (Figure 4.4) was analysed using a 3 group (Control, 2-back, Stroop) by 4 block (1, 2, 3, 4) by 5 time (minutes 1, 2, 3, 4, 5) ANOVA on the average percentage of MVC force produced per second. This revealed main effects for group, $F_{2,87}$ = 3.41, *p*<.05, $\eta^2$=.07, and block, $F_{3,85}$ = 41.47, *p*<.001, $\eta^2$=.59. Post-hoc analysis confirmed that the control group produced more force than the 2-back in blocks 2, 3 and 4 and blocks 2 and 3 for the Stroop group. Pacing strategy was analysed using a 3 group (Control, 2back, Stroop) by 4-block (1, 2, 3, 4) by 5-time (minutes 1, 2, 3, 4, 5) ANOVA on the percentage of total force produced per minute. This yielded a main effect for time, $F_{4,84}$ = 62.92, *p*<.001, $\eta^2$=.75, and a block-by-time interaction effect, $F_{12,76}$ =

3.92, *p*<.001, $\eta^2$=.38; force production declined as the blocks progressed. Importantly, there were no differences in pacing strategy among the groups.

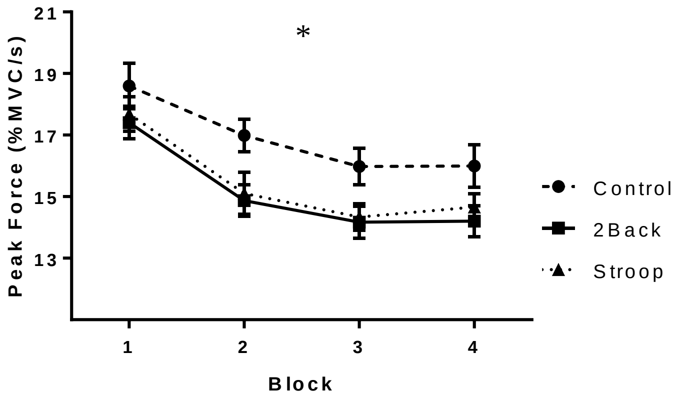


**Figure 4.4** Effect of the cognitive group task on the physical performance in the 5-minute handgrip task over 4 repeated blocks. * (*p*<.05) Significant main effect of group. $ (*p*<.001) Significant main effect of block. Data presented as M ± SEM.

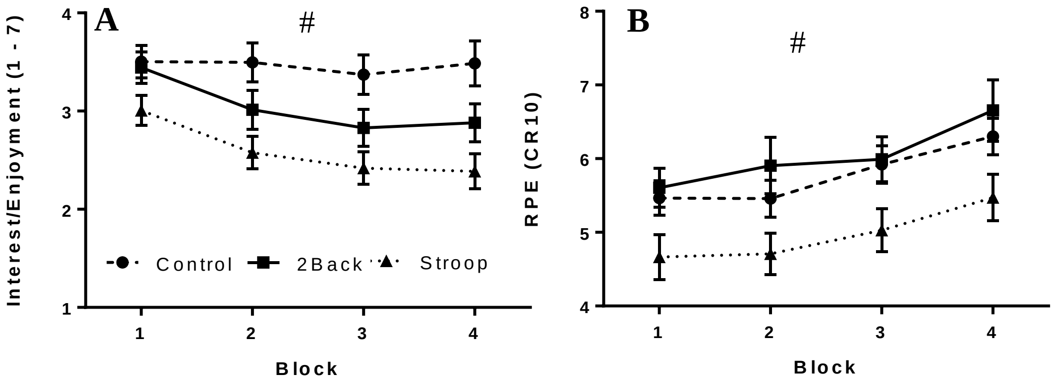


**Figure. 4.5** Effect of the physical task on the psychological self-report ratings interest/enjoyment (A) and RPE (B) over 4 repeated blocks for each cognitive group. # (*p*<.05) Significant main effect of block. * (*p*<.05) Significant main effect of group. Data presented as M ± SEM.

### 4.4.5 Physical task - Psychological ratings

The interest/enjoyment and RPE ratings for the physical tasks (Figure 4.5) were analysed with 3 group (Control, 2-back, Stroop) by 4 block (1, 2, 3, 4) ANOVAs. Main effects for group, $F_{2,87}$ = 6.83, *p*<.05, $\eta^2$=.14, and block, $F_{3,85}$ = 3.93, *p*<.001, $\eta^2$=.24, were noted for interest/enjoyment; the task was less interesting and enjoyable for the Stroop group than the control group. Main effects for group, $F_{2,87}$ = 3.54, *p*<.05, $\eta^2$=.08, and block, $F_{3,85}$ = 27.74, $p$<.001, $\eta^2$=.50, were found for RPE; perceived exertion was lower for the Stroop group than the control group. Finally, interest and enjoyment decreased whereas exertion increased with repeated task performance.

### 4.4.6 Physical task - Physiological measures

Cardiac activity during the physical tasks (Figure 4.6) were analysed with a series of 3 group (Control, 2-back, Stroop) by 4 block (1, 2, 3, 4) ANOVAs. A group main effect was found for HR, $F_{2,87}$ = 3.15, $p$<.05, $\eta^2$=.07, which was faster in the control group than the 2-back group. Block main effects were found for HR, $F_{3,85}$ = 33.20, $p$<.001, $\eta^2$=.54, and RMSSD, $F_{3,85}$ = 13.47, $p$<.001, $\eta^2$=.32. HR values decreased and RMSSD increased from block 1 to 3. Muscle activity during the exercise task (Figure 4.7) was tested using 3 group (Control, 2-back, Stroop) by 4 block (1, 2, 3, 4) ANOVAs. There were main effects for block for the extensor carpi radialis, $F_{3,76}$ = 6.36, $p$<.001, $\eta^2$=.20, and flexor carpi ulnaris, $F_{2,78}$ = 4.58, $p$<.05, $\eta^2$=.11, forearm muscles which tended to decrease as the blocks progressed. It is worth noting that no group differences were detected in heart rate variability and muscle activity.

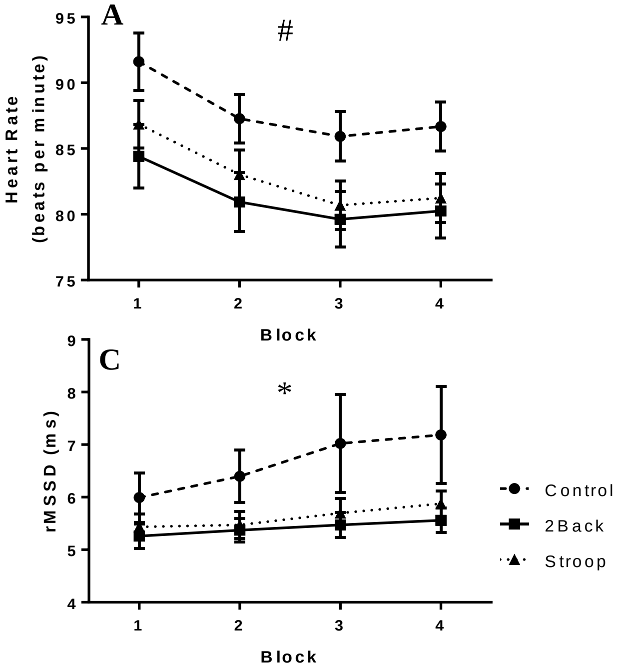


**Figure 4.6** Effect of the physical task on the physiological cardiac response measures of HR (A) and HRV, SDNN (B) and rMSSD (C) over 4 repeated blocks for each cognitive task group. # (p<.05) Significant main effect of group. * (p<.001) Significant main effect of block. Data presented as M ± SEM.

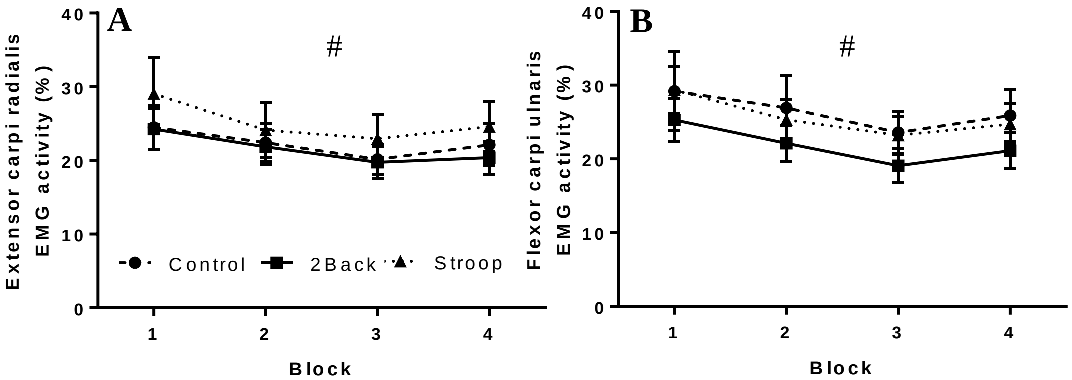


**Figure 4.7** Effect of the physical task on the rectified EMG muscle activity as a percentage of activity during MVC in the extensor carpi radialis (A) and flexor carpi ulnaris (B) over 4 repeated blocks for each cognitive task group. # (*p*<.05) Significant main effect of block. Data presented as M ± SEM.

## 4.5 Discussion

This is the first study to investigate the temporal and task effects of prior engagement in mentally demanding cognitive tasks on subsequent muscular endurance performance using a dynamic rhythmic handgrip exercise task. The study had three specific aims. The first was to assess the effects of a cognitively demanding task, with and without response inhibition, on psychological and physiological indices of mental fatigue as a function of time. The second was to investigate the effects of cognitive tasks on subsequent performance on a dynamic rhythmic muscular endurance task as a function of time. The third was to investigate the effects of cognitive tasks on psychological and physiological measures during the muscular endurance task as a function of time.

The first study aim was to assess the effects of a cognitively demanding task (with and without response inhibition) on psychological and physiological indices of mental fatigue as a function of time. In support of our hypothesis, participants reported greater mental fatigue, general fatigue and mental exertion following both cognitive tasks relative to watching the documentary film. The subjective ratings of mental fatigue increased threefold after 40 accumulated minutes of cognitive task engagement. The magnitude of increase in fatigue is in line with previous research that utilised visual analogue scales to assess ratings of mental fatigue following 45 minutes of an incongruent colour word Stroop task [12] and 120 minutes of a 2-back task [41]. Unfortunately, no insight into the development of mental fatigue over time can be determined from the previous studies as participants only reported their subjective ratings upon completion of the cognitive tasks. In contrast, the current study observed an increase in mental fatigue after the first task block which then increased linearly across the four blocks, indicating that 10 minutes of working memory and word interference tasks are sufficient to induce a state of mental fatigue, as indicated by self-report measures. That this effect occurred to the same extent in the 2-back and Stroop tasks indicates that mental fatigue can be induced by cognitive processing that does not need to involve response inhibition. This argument is supported by previous findings demonstrating the same increases in mental fatigue, following 45 minutes of a PVT, which does not require response inhibition, as the AX-CPT and colour word Stroop tests, which do require response inhibition [12]. In sum, response inhibition is sufficient rather than necessary for fatigue-induced performance detriments.

To investigate the physiological responses to mental fatigue, cardiac activity was measured during the cognitive tasks. HR was higher and HRV lower during the cognitive tasks relative to control, indicative of less mental effort [42]. There were no differences between the 2-back and Stroop groups, illustrating that effortful cognitive tasks that elicit changes in cardiac responses are independent of response inhibition processes. The finding that HR decreased and HRV increased as the blocks progressed for all three groups indicates that the impact of mental effort on cardiac response waned with time. This observation, which is contrary to the first hypothesis, is likely to be due to increased task familiarity with exposure. A similar gradual time-related increase in HRV has been reported in participants who engaged in mentally fatiguing Sudoku puzzles for 120 minutes [43]. Decreases in parasympathetic and increases in sympathetic activities have been observed by Tanaka and colleagues following one 30-minute block [8] and four 30-minute blocks [41] of a 2-back task. In the single 30-minute block study, HRV measures were averaged over 5-minute epochs, and showed decreased vagal nerve activity after 10 minutes, which then plateaued for the remaining 20 minutes of the 2-back test. In the current experiment it is possible that the short breaks between the cognitive tasks, imposed by the physical task (5 minutes) and self-report questionnaires (c. 1 minute), in conjunction with increased task familiarity, contributed to the increased HRV as the blocks progressed. No differences in the HRV measures in the low and high spectral bands were found relative to baseline assessment following 45 minutes of engagement in a variety of cognitive tasks [12], which could represent a transient nature of mental effort and HRV changes. However, when analysed over 5-minute blocks within the task, the PVT non-response inhibition task had a higher level of sympathetic activity relative to the response inhibition cognitive tasks. The authors suggest that this could be due to an increased attentional focus due to the demands of the PVT relative to the inter-stimulus Stroop and AX-CPT response inhibition tasks. The short breaks between presented stimuli in these tasks permit lapses in attentional focus [44] and reduced cardiac response. The discrepancy in HRV during the Stroop task between this study and the current study could be due to differences in the test. In our study, participants verbally stated the colour of the word font rather than indicate the correct answer with a press of a button selected from 2 possible answers. Verbally stating the word could be more representative of response inhibition as a more natural reaction to a written word is to read and state it rather than press a button. Additionally, in this study all trials were incongruent whereas in the previous experiment half of the presented words were incongruent and half were congruent. In sum, there is a casual relationship between decreased HRV, suggestive of increased mental effort, for cognitive tasks independent of response inhibition, which reduces as a function of time. The first experimental aim was to assess the effects of mentally demanding cognitive tasks on psychological and physiological indices of mental fatigue as a function of time. We have shown that progressive engagement in cognitive tasks requiring both inhibition and non-inhibition responses accentuates the psychological responses and attenuate the physiological responses.

The second study aim was to investigate the effects of cognitive tasks on subsequent performance on a dynamic rhythmic muscular endurance task as a function of time. In support of our second hypothesis we found that a mentally demanding cognitive task, with or without response inhibition, impaired subsequent muscular endurance performance. This decline in performance was not due to changes in pacing strategy, which was the same for all groups. This finding is consistent with experiments on whole-body endurance exercise [17,18]. Exercise performance did not deteriorate further over time in the cognitive task groups relative to the control group. This finding indicates that a state of mental fatigue can impair performance with no changes in the dose-response relationship between mental fatigue and exercise performance. This is the first study to demonstrate a minimum threshold of engagement, of at least 10 minutes, on a mentally demanding cognitive task to impair performance on a subsequent dynamic muscular endurance task. In comparison, a previous study reported that a 10-minute Stroop task did not impair subsequent shuttle run performance [45]. The shortest cognitive task duration to impair whole-body endurance exercise is 30 minutes [18] whereas only a few minutes of a cognitive task can impair submaximal isometric exercise [26,27]. In light of our second aim we found that a cognitive task, independent of response inhibition, needs to be at least 10 minutes to impair performance on subsequent dynamic muscular endurance in a rhythmic static task. This is due to no performance effect after block 1 and falls between the thresholds reported in the literature for isometric (a few minutes) and whole-body (half an hour) endurance exercise.

The third study aim was to investigate the effects of cognitive tasks on psychological and physiological measures during the endurance task as a function of time. Compared to the cognitive task groups, the control group reported more interest and enjoyment during the physical tasks and less interest and enjoyment during the cognitive tasks. These group differences in interest and enjoyment, an indirect measure of intrinsic motivation [46], indicate that the impaired exercise performance of the 2-back and Stroop groups may have been due to a decline in the desire to perform to the best of their ability. Performance-related monetary reward, should have increased extrinsic motivation and could have decreased intrinsic motivation [47], however, this was offered to all participants, and, therefore, it cannot explain the group differences in interest and enjoyment. Participants were instructed to generate as much force as possible during the physical task, which would require maximal effort. The Stroop group reported lower RPE ratings relative to the other two groups, which could be reflective of the lower physical performance relative to the control group and contrasts with our hypothesis and findings from previous experiments where RPE is elevated following response inhibition tasks in TT performance tasks [17,18]. Also, in contrast with our hypothesis we observed that heart rate and muscle activity declined over the blocks in all the groups in line with the lower force production. The control group's HR was higher during the physical tasks, which is reflective of their higher force production. The HRV measures in the higher spectral band indicted a reduced mental effort as the blocks progressed. We did not observe elevated EMG muscle activity following cognitive task engagement. This finding is contrary to previous research with isometric handgrip [26] and whole-body cycling exercise [24], and could be due to either the intermittent nature of the dynamic rhythmic handgrip task and/or the duration of the cognitive tasks.

#### 4.5.1 Limitations

This study has provided evidence concerning the time course of the development of mental fatigue and its effects on muscular endurance performance. The findings should be interpreted in light of a number of possible study limitations. First, it is possible that the development of mental fatigue, as indicated by both psychological and physiological measures over time, could be attenuated due to the 5 minute physical task at the end of each block. Second, the performance deterioration in the 2-back and Stroop groups could be due to reduced extrinsic motivation as this construct was not measured. However, this is unlikely as monetary reward was offered to the participants to ensure that they motivated for the tasks. Finally, the study examined the effects of a cognitive task on rhythmic static exercise performance. Care must be taken when generalizing from a muscular endurance task to whole-body endurance and isometric muscular endurance tasks.

### 4.5.2 Future directions

The present study has demonstrated that at least 10 minutes of a mentally demanding cognitive task can impair performance on a subsequent dynamic and rhythmic muscular endurance task. It would be interesting to investigate the impact of shorter cognitive task durations on whole-body endurance exercise. Similarly, as most of the previous research on the impact of mental fatigue on whole-body and muscular endurance exercise performance has utilised response inhibition tasks, cognitive tasks without response inhibition should be further examined.

The role of mental fatigue on physical activity should be of interest in any job which requires a high level of task performance in effortful cognitive and physical tasks, such as the military, emergency services and construction workers. It has been hypothesised that building resilience to the negative effects of mental fatigue can reduce RPE for the same absolute exercise intensity and improve endurance exercise performance and has been referred to as brain endurance training (BET) [48]. This involves the systematic repetition of mentally demanding cognitive tasks alongside physical endurance training to place an extra stressful mental stimulus onto an individual which raises their RPE and improves physical performance when the cognitive task is removed. Dynamic rhythmic handgrip exercise could be incorporated with mentally demanding cognitive tasks as a practical task to investigate the efficacy of BET and its underlying physiological mechanisms.

### 4.5.3 Conclusion

In agreement with previous research the present study has shown that performing a cognitive task for 10 minutes induces a state of mental fatigue. After 20 minutes this state of mental fatigue will impair exercise performance. This is the first study to confirm this effect in a dynamic rhythmic muscular endurance task. Importantly, the study showed that the effects on endurance are the same for 2-back and Stroop tasks, indicating that the cognitive task does not need to involve response inhibition to impair exercise performance. Future research should seek to confirm these observations in isometric and whole-body endurance exercise tasks.

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5

# Brain endurance training

## 5.1 Abstract

**Introduction:** Mental fatigue (MF) impairs endurance exercise. Brain endurance training (BET) – such as engaging in cognitive tasks during exercise – can develop resilience to MF and improve physical performance compared to physical training alone. The mechanism for this effect is unknown.

**Objectives:** To examine if BET enhances performance over physical training and investigate any underlying physiological mechanisms.

**Methods:** Pre- and post-testing: 36 participants completed dynamic rhythmic muscular endurance handgrip tasks requiring generation of as much force as possible once a second for 300 s, performed under 3 counterbalanced conditions: following 600 s of a 2-back memory/attention task (subsequent); while performing a 2-back task (concurrent); and on its own (solo). Cardiac activity (ECG), electromyographic (EMG) forearm activity, pre-frontal cerebral haemodynamics (near infrared spectroscopy), and force were recorded. Training: Participants (randomised to a Control or BET group) completed 24 (6 weeks) submaximal hand contractions sessions. The BET group also completed concurrent cognitive tasks (2-back, word incongruence Stroop). Measures of motivation, physical and mental exertion and mental fatigue were collected throughout.

**Results:** Endurance performance, across the 3 tasks, improved more following BET (32%) than Control (12%) ($p<.05$). The cognitive component of the concurrent and subsequent task improved more in BET (7%) than Control (1%) ($p<.05$). Increased performance in BET occurred with a higher PFC oxygenation during the post-training physical tasks over time relative to Control ($p<.05$).

**Conclusion:** BET improves endurance performance over physical training alone was associated with a training-induced maintenance of PFC oxygenation, suggestive of reduced mental effort during physical activity.

## 5.2 Introduction

The role of the brain in the regulation of endurance exercise has garnered increased interest following Noakes's proposal of the *central governor model* in 1996 [1]. The past two decades has seen this theory developed [2–7], debated [8–11], and challenged by alternative accounts [10,12–15]. Despite differences among the competing models, all recognise the importance of perceived effort, emotion, and neural-cognitive processing as determinants of performance. Mental fatigue, defined as a "psychobiological state caused by prolonged periods of demanding cognitive activity and characterised by subjective feelings of tiredness and a lack of energy" [16], can impair endurance exercise [17] and skilled motor performance [18]. Accordingly, individuals should avoid mental fatigue when wishing to achieve optimal physical performance and performing activities associated with high cognitive and physical demands, such as those facing the military and rescue services [19].

Marcora and colleagues [16] demonstrated that inducing mental fatigue reduces time to exhaustion by 18%, together with a higher rate of perceived exertion (RPE), without any differences in blood lactate, respiratory and cardiovascular activity, compared to control. Although the neurophysiological mechanism underlying this fatigue-related effect has yet to be established, several candidates have been proposed, including changes to muscle and brain function. Electromyographic (EMG) recordings confirm increased knee extensor muscle activity during an endurance cycling task whilst mentally fatigued [20] and increased flexor muscles during a submaximal isometric handgrip task after completing a mentally fatiguing response inhibition task [21]. Reduced oxygenated haemoglobin levels in the prefrontal cortex (PFC), suggestive of lower PFC activation, have been observed at exhaustion following a simultaneous submaximal handgrip and cognitive task relative to handgrip alone [22]. Based on the abovementioned evidence, any intervention which reduces RPE, while maintaining the same workload, should improve exercise performance.

Marcora [23] hypothesised that building resilience to the negative effects of mental fatigue by repetition of mentally fatiguing tasks would reduce RPE and thereby improve endurance performance. He introduced the term *brain endurance training* (BET) to describe such fatigue inoculation interventions. Marcora tested this hypothesis by comparing a control group, who completed 12 weeks of cycle training (3 times a week at 65% $VO_2$max for 60 minutes), and a BET group who simultaneously completed a mentally demanding cognitive task with the cycle training. Both groups exhibited similar increases in $VO_2$max from pre- to post-training, presumably due to the same volume of exercise. Notably, however, time to exhaustion (cycling at 75% of $VO_2$max) increased by 113% in the BET compared to 43% in the control group, coupled with a reduction in RPE. To date, this is the only evidence, to our knowledge, that demonstrates the effectiveness of BET.

Building on this new finding, we undertook the current study with two purposes. First, to replicate the performance enhancement effect of BET. Second, to investigate underlying physiological mechanisms involving pre-frontal cortex oxygenation, muscle activation patterns, and cardiac responses.

## 5.3 Methods

### 5.3.1 Experimental design

Our study employed a mixed experimental design, with group (BET, control) as the between-participant factor, and both test (pre-test, post-test) and task (solo, subsequent, concurrent) as within-participant factors. Participants attended 26 sessions over eight weeks, consisting of a pre-test (week one), 24 training sessions (weeks two to seven) and post-test (week eight) as shown in figure 5.1.


**Figure 5.1** Brain endurance training experiment protocol

### 5.3.2 Participants

Participants were 36 (15 females, 21 males) healthy undergraduate students aged 20 ± 2 years. Exclusion criteria included dominant hand injury and changes to habitual exercise activity during the study. In the 24-hours prior to the pre-test and post-test, participants were requested to abstain from vigorous exercise and alcohol consumption, and to sleep for seven hours. They were asked to refrain from eating (one hour) and caffeine (three hours) before all sessions. Using a randomised control trial design, participants were randomly assigned to either a control group (*n* = 18) or BET group (*n* = 18). Ethical approval was obtained from the University of Birmingham Research Ethics committee. Informed consent was obtained from all individual participants included in the study. All received a £50 voucher and course credit.

### 5.3.3 Pre- and post-test

Following instrumentation, determination of MVC [24], and one minute of task familiarisation (both physical and cognitive components), participants completed a 5-min endurance task under three counterbalanced conditions. In each task, participants were asked to generate as much force as possible by squeezing a handgrip dynamometer with their dominant hand once per second as cued by a metronome. The three tasks were completed: 1) following 600 s of a 2-back [25] working memory task (subsequent); 2) while performing a 2-back task (concurrent), and 3) on its own (solo). The post-test session was identical to the pre-test but with the addition of a novel cognitive task following the 3 physical performance tasks. the testing protocol is shown in figure 5.2.

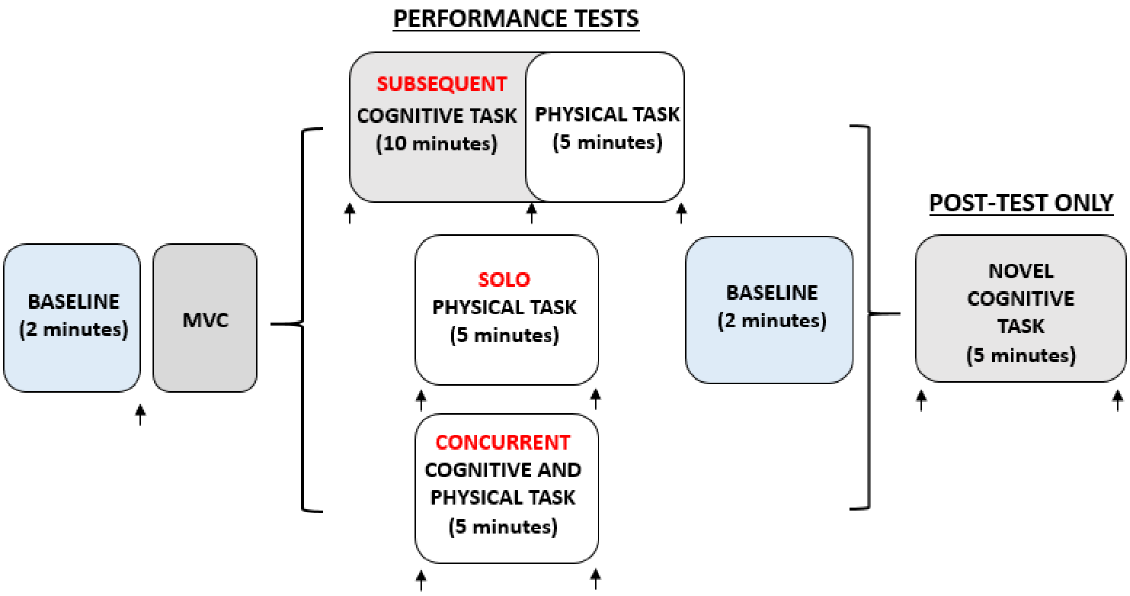


**Figure 5.2** Testing protocol (Arrows indicate timing of ratings questionnaires)

Participants completed the 2-back test for a period of 10 minutes in the pre- and post-testing session prior to the physical task in the subsequent condition. The 2-back test involves working memory but does not involve response inhibition [26]. The 2-back task presented a random consonant in the centre of a computer monitor for half a second followed by a blank display for three seconds requiring participants to respond indicating if the current letter displayed was the same (target) or different (non-target) as the letter displayed two previously using a computer keyboard with their non-dominant hand. Letters were displayed with a 1:2 target to non-target ratio. Performance was determined by the percentage correct responses. Participants were verbally briefed on the task and presented with written instructions (Figure 5.3) prior to the familiarisation period and performance task.

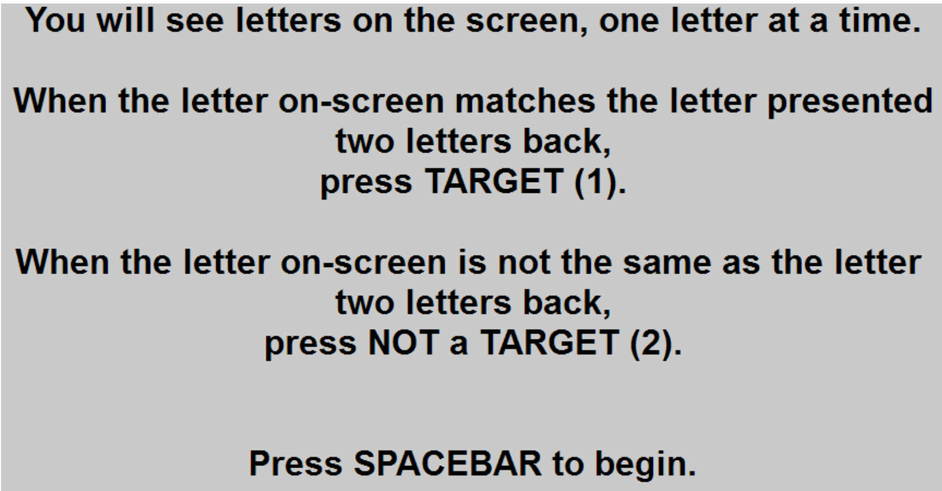


**Figure 5.3** Pre- and post-test subsequent 2-back cognitive task instructions

The post-testing session novel cognitive task was a 5-minute number incongruent Stroop task. Participants were required to indicate how many words were displayed from a list of number words (between one and four) of the same type (e.g. two, two, two); the correct answer was the number of words in the list (e.g., three) whereas the incorrect answer included the number that the words represented (e.g., two). The two possible answers (e.g., ‘two’ or ‘three’) were displayed in black font in the bottom left and right corners of the display, and participants responded with either a left (Z) or right (/) keyboard button press. Participants received verbal and written instructions (figure 5.4) prior to the task. Performance was measured by the response time (ms) and accuracy (% correct).

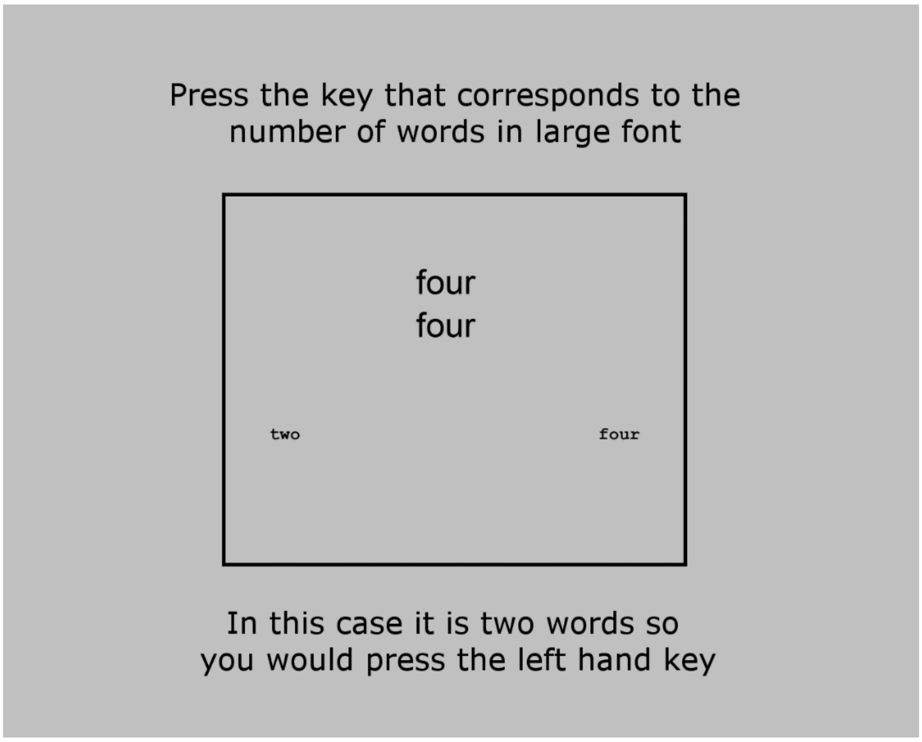


**Figure 5.4** Incongruent number word Stroop instructions

### 5.3.4 Physiological measures

Force (N) was recorded continuously through the testing and training sessions. In the three pre- and post-test physical performance tasks the absolute force generated was calculated from the area under the force-time curve of each squeeze and averaged over 30-s intervals. All other physiological measures were recorded only in the test sessions.

An electrocardiogram was recorded using surface electrodes in a modified chest configuration and an amplifier (509, Morgan, USA). Heart rate variability (HRV) measures were used as indicators of effort and stress. HRV was calculated from the R-to-

R wave interval period for each minute of the pre- and post-testing tasks. The root mean square of the successive differences (RMSSD) and the standard deviation (SDNN) of the R-to-R wave interval were calculated (for further detail see Cooke et al [24]).

The electromyographic (EMG) activity of extensor and flexor carpi radialis forearm muscles were recorded using differential surface electrodes and an amplifier (Bagnoli-2, Delsys, USA). The EMG signals were rectified, averaged over 30 s, and normalised as a percentage of EMG during MVC. Prefrontal cortical haemodynamics were assessed using near infra-red spectroscopy (NIRS; NIRO-200NX, Hamamatsu Photonics KK, Japan).

The NIRO-200 device measures changes in chromophore concentrations of oxyhaemoglobin and deoxyhaemoglobin (ΔO2Hb and ΔHHb) via the modified Beer-Lambert law and provides depth-resolved measures of tissue $O_2$ saturation [total oxygenation index (TOI)] and tissue Hb content (i.e., relative value of the total haemoglobin normalized to the initial value, nTHI) using the spatially resolved spectroscopy (SRS) method. The SRS-derived NIRS parameters limit contamination from superficial tissue via depth-resolved algorithmic methods, providing an index of targeted local tissue saturation (TOI) and perfusion (nTHI), see Davies et al. [27] for a recent review. Probes were enclosed in light-shielding rubber housing that maintained emitter-to-detector optode spacing (4 cm), positioned over the right pre-frontal electrode site (Fp2 in 10-20 system) [28] and secured to the head. Before each task participants were instructed to sit still, relax, clear their mind and look at a fixation cross for 2 minutes. Measures of TOI, nTHI, $O_2$Hb and HHb were averaged over 30 s calculated relative to the last 30 s of the prior baseline.

All signals were acquired via a Power 1401 (Cambridge Electric Design Limited, UK) digital-to-analogue convertor (16-bit resolution, 2.5 kHz sample rate) running Spike2 (version 6.06) software.

### 5.3.5 Psychological measures

Success motivation [29] was measured prior to each task using a 5-point scale with anchors of "0 = not at all" and "4 = extremely"; example items included "I will be disappointed if I fail to do well on this task" and "I am eager to do well". Exertion and fatigue were measured following each task using 11-point scales: the mental exertion (ME) scale had anchors of "0 = nothing at all" and "10 = maximal mental exertion" whereas the mental fatigue (MF) scale had anchors of "0 = nothing at all" and "10 = totally exhausted". A baseline measure of MF was also taken. Following each task, interest and enjoyment [30] were measured using a 7-point scale with anchors of "1 = not true at all" and "7 = very true", with example items including "I enjoyed doing this activity very much" for enjoyment and "I would describe this activity as very interesting" for interest. RPE [31] was measured every minute during the solo and subsequent tasks and after the training sessions.

### 5.3.6 Training

#### 5.3.6.1 Physical tasks

The physical task required participants to squeeze the handgrip dynamometer once per second (cued by metronome) at approximately 30% MVC until they reached a pre-determined cumulative force production target. Target attainment was calculated by summing the force generated, normalised to MVC, every second. Based on pilot testing, the initial target was 12000 (1 unit representing 1% MVC a second), which incremented

500 points every week (every fifth session) to account for training-related improvements in strength. 6-weeks of rhythmic handgrip training at 30% MVC has been shown to substantially improve muscular endurance performance [32]. Every fourth session, participants completed the first 5000 points as quickly as possible to replicate the solo task (described above). In session one, visual feedback was provided in the first five minutes for guidance. The BET group completed the computer-based cognitive tasks using a mouse in their non-dominant hand; tasks became progressively more difficult each week. Training session time and psychological self-report measures were averaged each week in conjunction with the progressive physical and cognitive task demands.

#### 5.3.6.2 Cognitive tasks

The cognitive tasks during the training period for the BET group consisted of the pre-test concurrent 2-back (sessions 1-4, 9, 11), colour word Stroop (sessions 5-8, 10, 12) , modified colour word Stroop (sessions 13,14,15,16), 2-back test with a 2500 ms letter refresh rate (sessions 17,18,19,20) and double incongruent colour word Stroop task (sessions 21,22,23,24). The colour word Stroop [33] required participants to indicate the font colour (red, blue, green and yellow) of a colour word from two possible answers displayed in a black font in the bottom left and right corners of the display with a corresponding left or right mouse click. Participants received verbal and written instructions (figure 5.3 and figure 5,4 for the 2-back and Stroop tasks respectively) displayed to participants prior to the training tasks. The modified version displayed answers in a green font whereas the double incongruent version presented the incorrect answer in a random colour and the correct answer in the same colour of the word presented. The incongruent Stroop colour-word test [34] involves working memory and response inhibition [35]. Performance was measured by response time and accuracy. For all Stroop tasks the stimulus was presented for 2500 ms or until a response was given followed by a fixation cross for 500 ms. All cognitive tasks were implemented using E-Studio (Psychology Software Tools, USA).

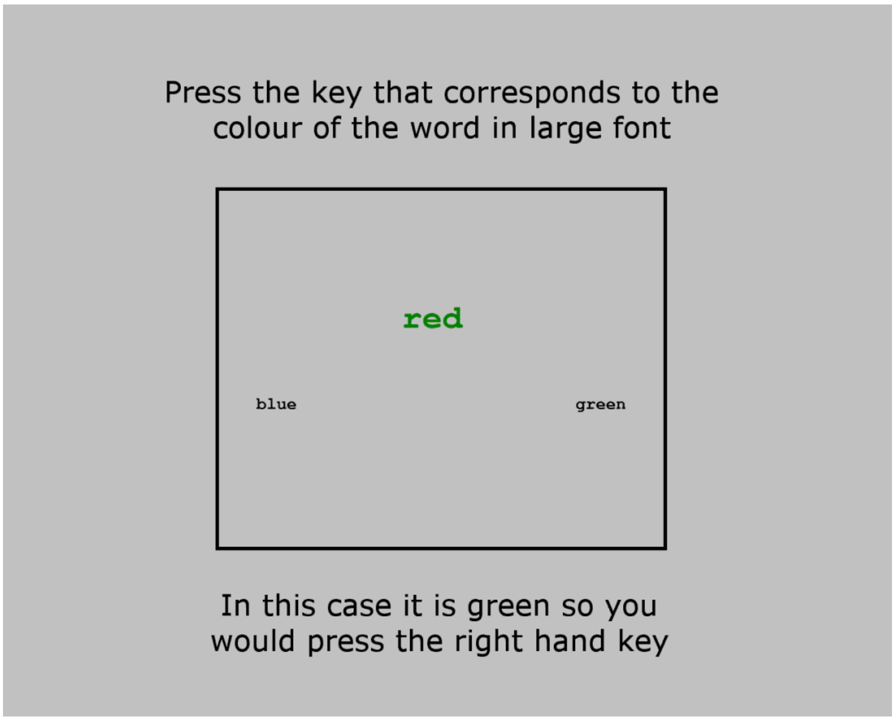


**Figure 5.5** Incongruent colour word Stroop instructions

### 5.3.7 Statistical analysis

Statistical analysis was carried out using SPSS 24 software (SPSS: An IBM Company, Chicago, IL, United States). Statistical significance was set at $p$<.05. All data values were expressed as mean ± standard deviation of the mean (M ± SD) unless otherwise stated. Partial eta-squared ($\eta_p^2$) was reported as the effect size, with values of 0.02, 0.13 and 0.26 indicating small, medium and large effects, respectively [36].

## 5.4 Results

### 5.4.1 Training

A series of 2 group (BET, control) by 6 training week (1, 2, 3, 4, 5, 6) ANOVAs revealed main effects for group on post-training MF ($F_{1,34}$ = 12.72, $p$<.001, $\eta^2$=.27) and ME ($F_{1,34}$ = 45.99, $p$<.05, $\eta^2$=.58), with ratings higher in BET (MF = 3.7 ± 1.4, ME = 4.3 ± 1.6) than control (MF = 2.2 ± 1.4, ME = 1.7 ± 1.4). Importantly, there were no group differences in average weekly training time (940 ± 159 s), RPE (5.5 ± 1.5), baseline MF (2.1 ± 1.2) or interest/enjoyment (3.1 ± 0.6).

### 5.4.2 Performance

A 2 group (BET, control) by 2 test (pre, post) ANOVA on MVC revealed a main effect for test ($F_{1, 34}$ = 66.26, $p$<.001, $\eta^2$=.66), with maximal force increasing from 421 ± 99 N pre-test to 485 ±116 N post-test. There were no group interaction effects indicating that MVC improvements were common to both groups. Absolute physical task performance was analysed with a 2 group (BET, Control) by 2 test (pre, post) by 3 task (subsequent, solo, concurrent) by 10 time (30-s averages) ANOVA on force produced per second, revealing a group-by-test interaction effect ($F_{1,34}$ = 6.064, $p$<.05, $\eta^2$=.15). The BET group showed a greater increase in force production (Figure 5.6) from pre-to-post (Δ = 32%) than the control group (Δ = 12%). A 2 group (BET, Control) by 2 test (pre, post) by 2 task (subsequent, concurrent) ANOVA on correct responses during the 2-back memory task yielded a group-by-test interaction effect ($F_{1,34}$= 4.56, $p$<.05, $\eta^2$=.12). The BET group improved their cognitive task performance, indexed by percent correct responses, in the subsequent task from 89 ± 4 % to 96 ± 3 % whilst the Control group improved from 87 ± 7 % to 90 ± 7.0 %. In the concurrent task, the BET group improved from 88 ± 6 % to 94 ± 5 % whereas Controls were unchanged from 86 ± 7 % to 85.0 ± 18 %. These values represent an overall improvement in working memory performance of 7 % for BET and 1 % for control. An independent samples t-test revealed no significant differences in the number of correct responses or accuracy in the novel cognitive task. The BET group trended (p=0.63) towards faster response times of 786 ± 129 compared to 864 ± 113 ms in the controls.

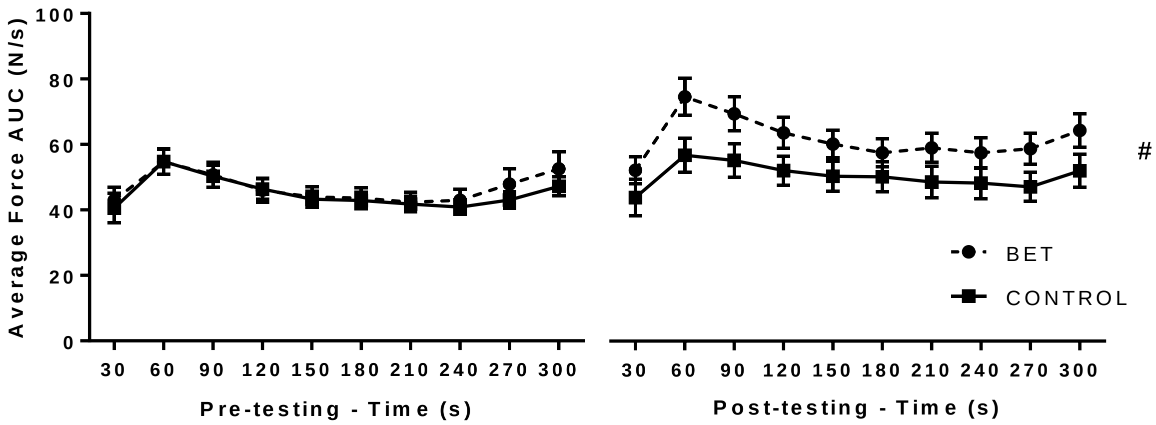


**Figure 5.6** Effect of brain endurance and physical training on absolute physical task performance averaged across the subsequent, concurrent and solo tasks. # ($p<.05$) Significant interaction effect of test-by-group. Data presented as M ± SEM.

### 5.4.3 Psychological state measures

A 2 group (BET, Control) by 2 test (pre, post) by 2 task (subsequent, solo) by 5 time (one minute averages) ANOVA on RPE revealed a test-by-task-by-time interaction effect ($F_{1, 34}$= 8.36, $p<.05$, $\eta^2$=.20) (Figure 5.7). A series of 2 group (BET, control) by 2 test (pre, post) by 3 task (subsequent, solo, concurrent) ANOVAs were conducted on self-reported interest, enjoyment, success motivation, ME and MF. These analyses yielded a test-by-task interaction effect for interest/enjoyment ($F_{1,34}$ = 9.21, $p<.05$, $\eta^2$=.21), dropping from 3.5 ± 0.9 to 2.6 ± 0.8 (subsequent), 3.8 ± 0.9 to 2.8 ± 0.8 (concurrent) and

3.4 ± 0.8 to 2.7 ± 0.8 (solo) and a group-by-test interaction ($F_{1,34}$ = 10.15, $p$<.05, $\eta^2$=.23), changing from 3.6 ± 1.2 to 2.3 ± 1.0 (BET) and 3.5 ± 1.2 to 3.1 ± 1.0 (Control); We also detected a test-by-task interaction effect for success motivation ($F_{1,34}$ = 10.70, $p$<.05, $\eta^2$=.24), reducing from 2.5 ± 0.9 to 2.3 ± 1.0 (subsequent), 2.5 ± 1.0 to 2.2 ± 1.0

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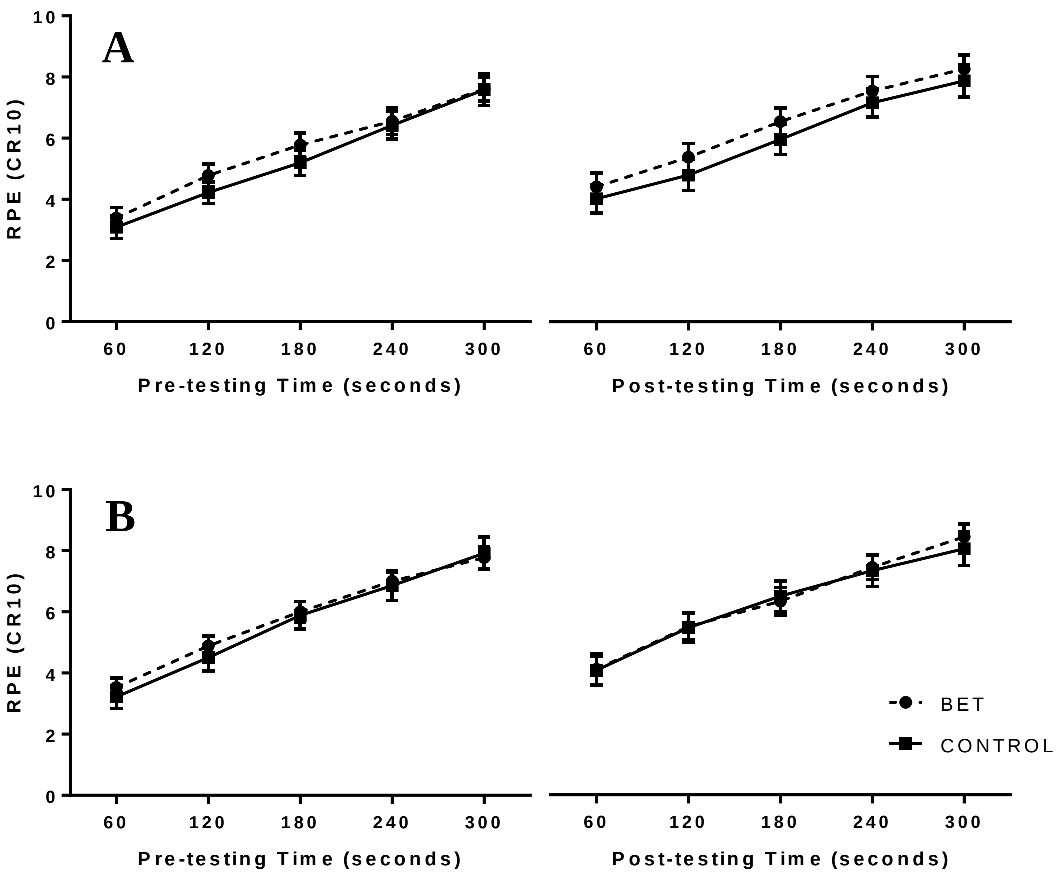


**Figure 5.7** Effect of brain endurance (BET) and physical training (Control) on RPE during the subsequent (A) and solo (B) tasks during pre-test and post-test. * Significant interaction effect of testing, time and task ($p$<.05). Data presented as M ± SEM.

### 5.4.4 Physiological measures

#### 5.4.4.1 Physical tasks

A series of 2 group (BET, Control) by 2 test (pre, post) by 2 task (subsequent, solo) by 10 time (30-s averages) ANOVAs were performed on the physiological measures. In the case of the prefrontal cortical haemodynamic response, ANOVA revealed a group-by-test-by-time interaction for TOI ($F_{1.34}$ = 5.35, $p$<.05, $\eta^2$=.14) (Figure 5.8), a group-by-test-by-task-by-time interaction for nTHI ($F_{1.34}$ = 4.84, $p$<.05, $\eta^2$=.13) (Figure 5.9), a group-by-task-by-time interaction for $O_2Hb$ ($F_{1.34}$ = 4.31, $p$<.001, $\eta^2$=.31) (Figure 5.10), and a task-by-time interaction for HHb ($F_{1.34}$ = 4.65 $p$<.05, $\eta^2$=.12) (Figure 5.11).

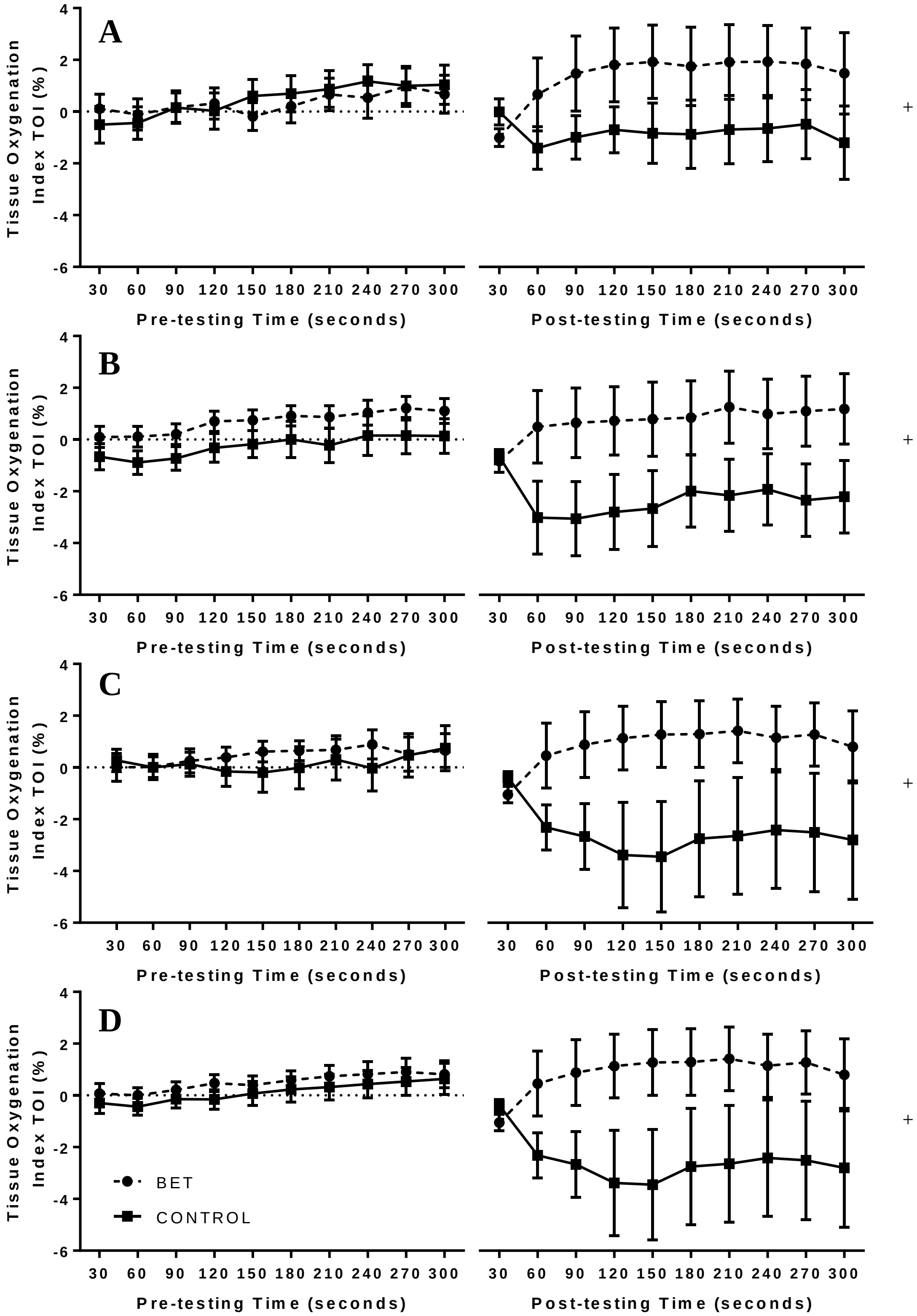


**Figure 5.8**. Effect of brain endurance and physical training on prefrontal cortex (indexed via total oxygenation index, TOI) during the subsequent (A), concurrent (B) solo (C) and all (D) tasks. + Significant ($p$<.05) interaction effect of group-by-test-by-time. Data presented as M ± SEM

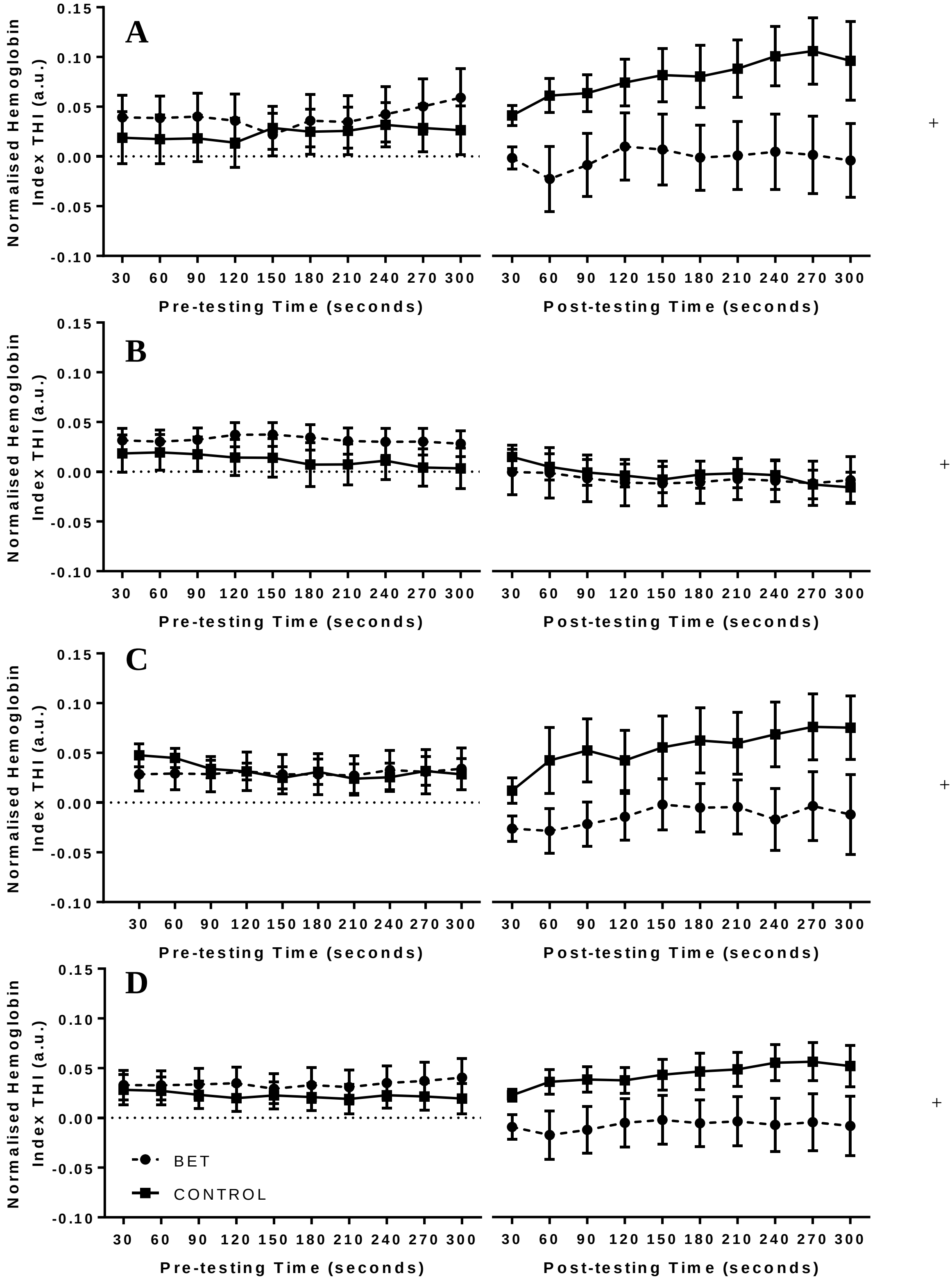


**Figure 5.9** Effect of brain endurance and physical training on prefrontal cortex total haemoglobin volume (indexed via normalised tissue haemoglobin index, nTHI) during the subsequent (A), concurrent (B) solo (C) and all (D) tasks. + Significant ($p$<.05) interaction effect of group-by-test-by-task-by-time. Data presented as M ± SEM.

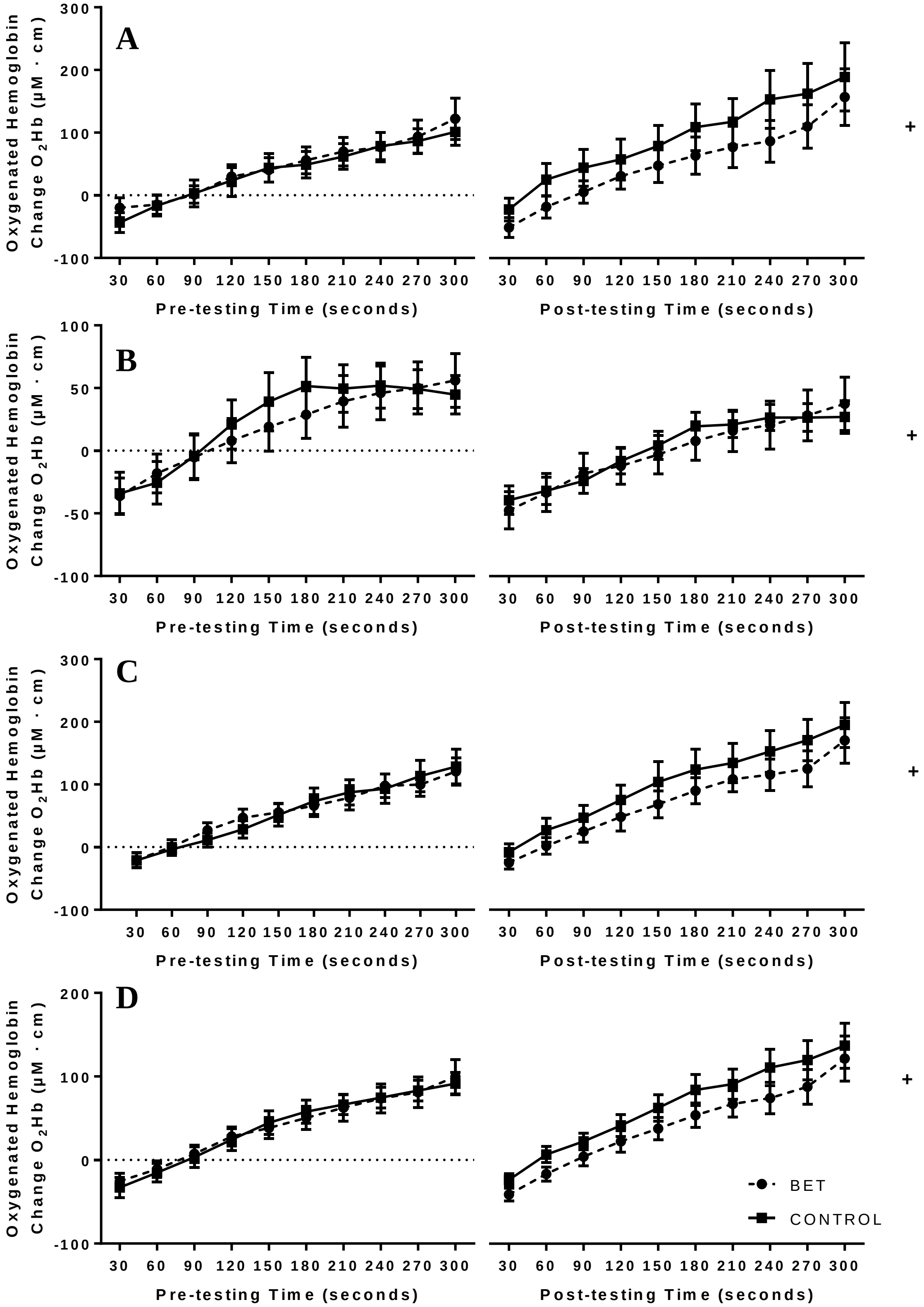


**Figure 5.10** Effect of brain endurance and physical training on prefrontal cortex oxyhaemoglobin volume ($O_2Hb$) during the subsequent (A), concurrent (B) solo (C) and all (D) tasks. + Significant ($p$<.05) interaction effect of group-by-task-by-time. Data presented as M ± SEM.

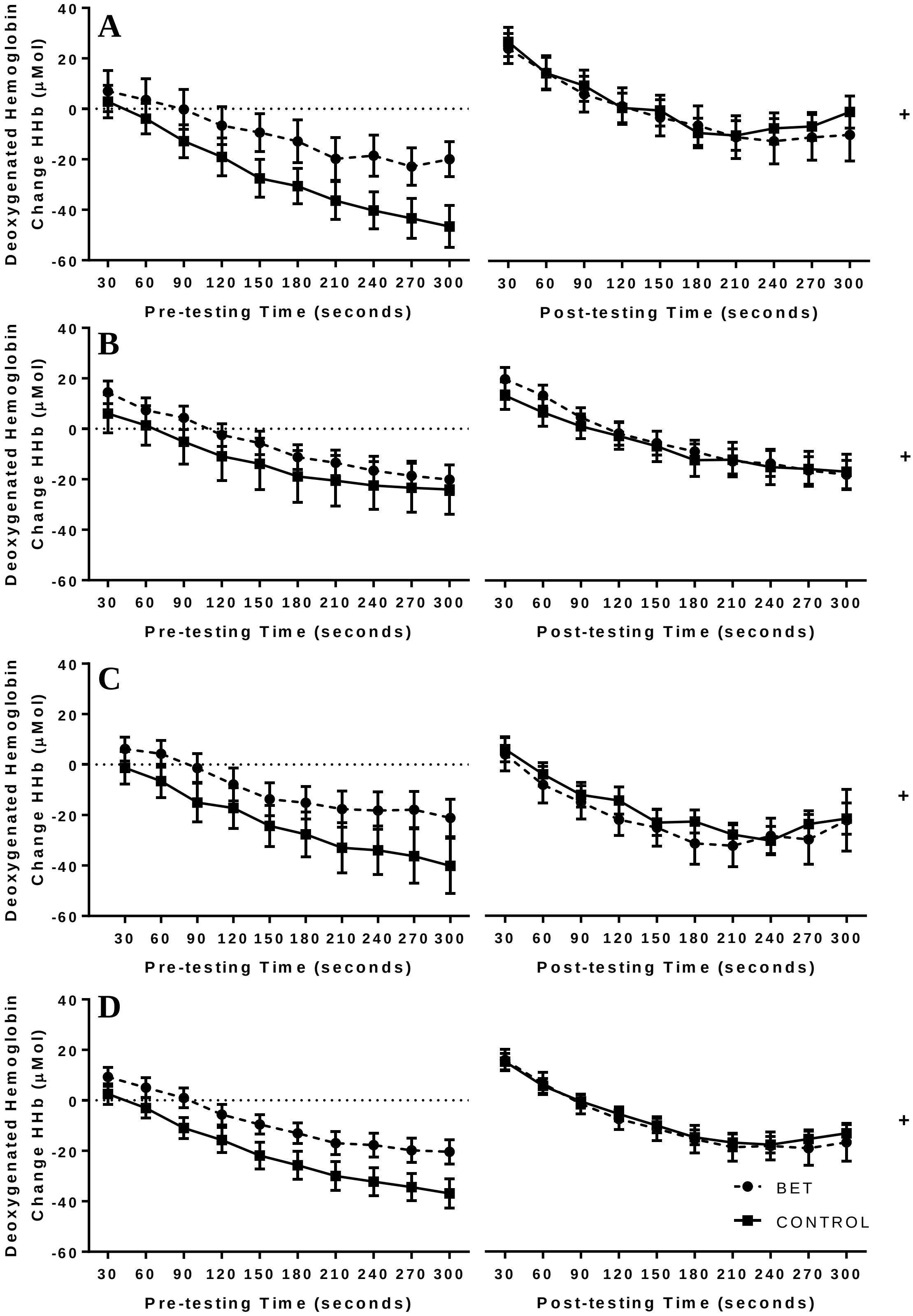


**Figure 5.11** Effect of brain endurance and physical training on prefrontal cortex deoxyhaemoglobin volume (HHb) during the subsequent (A), concurrent (B) solo (C) and all (D) tasks. + Significant (p<.05) interaction effect task-by-time. Data presented as M ± SEM.

Measures of electromyographic activity on the flexor carpi radialis and extensor carpi radialis for the three physical tasks were analysed with series of group (BET, control) by test (pre-test, post-test) by task (solo, subsequent, concurrent) by 10 time (30 s averages) mixed design ANOVAs. Results for the flexor carpi radialis (figure 5.12) revealed an interaction effect for test-by-task-by-time ($F_{18,61}$ = 1.68, $p$<.05, $\eta^2$=.0.05). Interaction effects were found for the extensor carpi unilaris (figure 5.13) for test-by-task ($F_{2,68}$ = 5.40, $p$<.05, $\eta^2$=.0.14) and task-by-time ($F_{18.61}$ = 4.37, $p$<.001, $\eta^2$=.0.11).

Measures of cardiac activity for the three physical tasks analysed with series of group (BET, control) by test (pre-test, post-test) by task (solo, subsequent, concurrent) by 5 time (60 s averages) mixed design ANOVAs. Results for HR (figure 5.14) revealed significant interaction effects for test by task ($F_{2,68}$ = 13.67, $p$<.001, $\eta^2$=.0.29), test by time ($F_{4,14}$ = 3.98, $p$<.05, $\eta^2$=.0.11) and task by time ($F_{8,27}$ = 13.81, $p$<0.001, $\eta^2$=.0.29). There were no main effects for group. Results for SDNN (figure 5.15) revealed a significant interaction effect for test by task ($F_{2,68}$ = 5.53, $p$<.05, $\eta^2$=.0.16) and test by time by group ($F_{2,34}$ = 2.59, $p$<.05, $\eta^2$=.0.07). The analysis for RMSSD (figure 5.16) yielded significant interaction effects for test by task ($F_{2,68}$ = 8.18, $p$=.001, $\eta^2$=.0.19) and test by time by group ($F_{4,34}$ = 3.69, $p$<.05, $\eta^2$=.0.10).

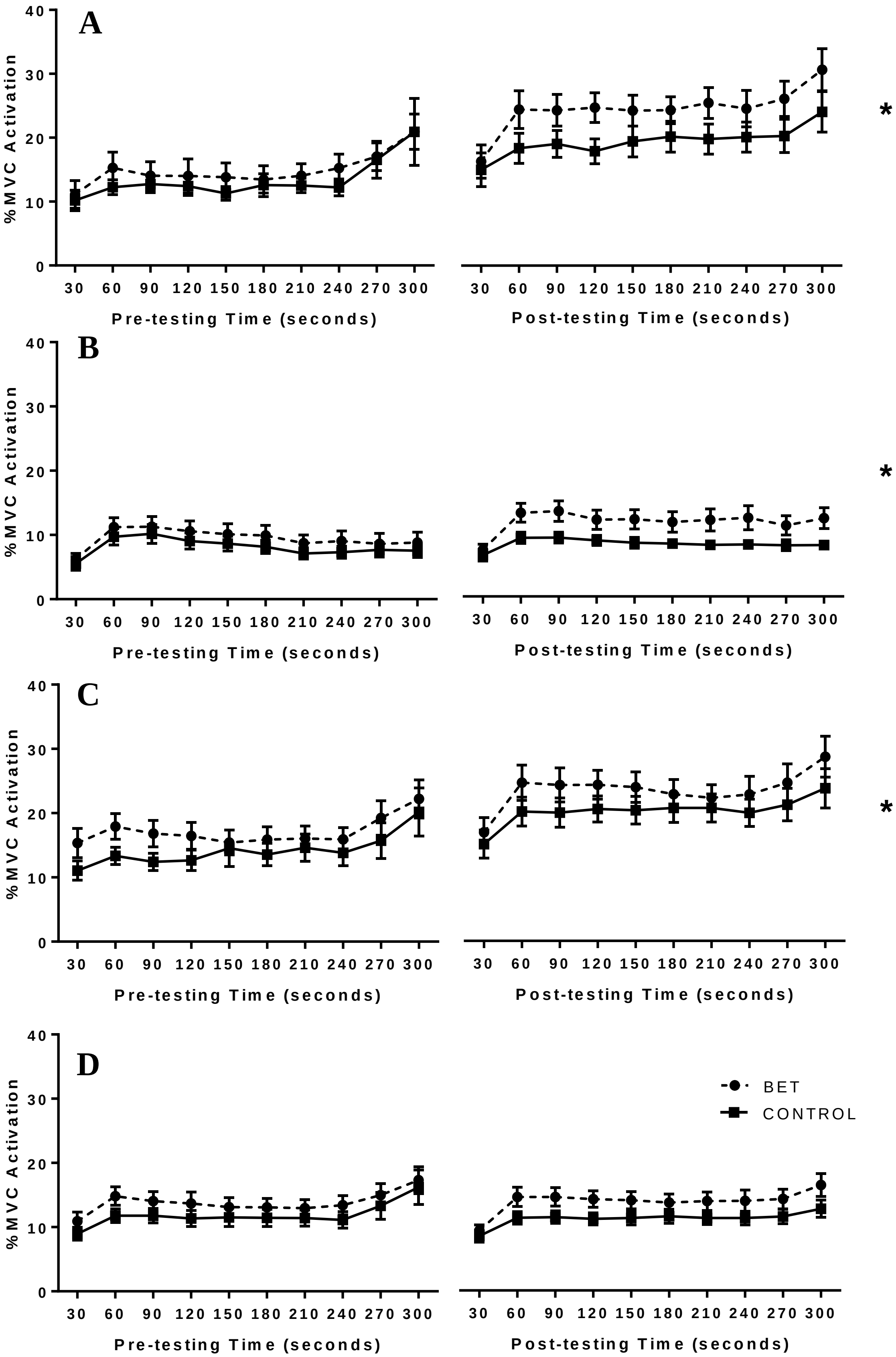


**Figure 5.12** Effect of brain endurance and physical training on flexor carpi radialis EMG muscle activity during the subsequent (A), concurrent (B) solo (C) and averaged across all tasks (D). * significant interaction effect for test-by-task-by-time ($p<.05$) with both the subsequent and solo tasks increasing more over time in the post test than the concurrent task. Data presented as M ± SEM.

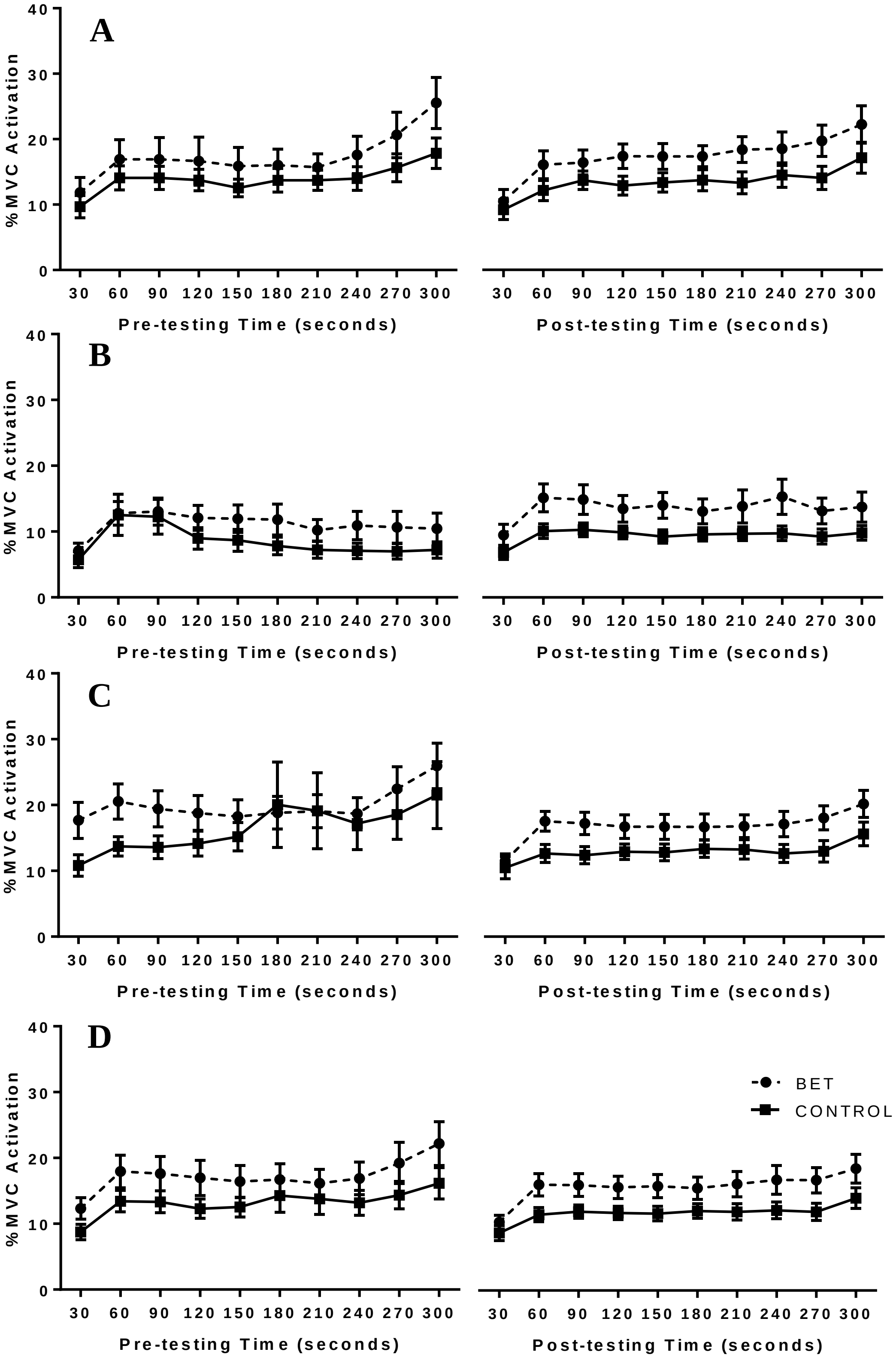


**Figure 5.13** Effect of brain endurance and physical training on extensor carpi unilaris EMG muscle activity during the subsequent (A), concurrent (B) solo (C) and averaged across all tasks (D). * Significant interaction effect of test-by-task (*p*<.05). # Significant interaction effect task-by-time *p*<.001). The concurrent task has lower activation levels in the post-test and over time than both the solo and subsequent tasks. Data presented as M ± SEM.

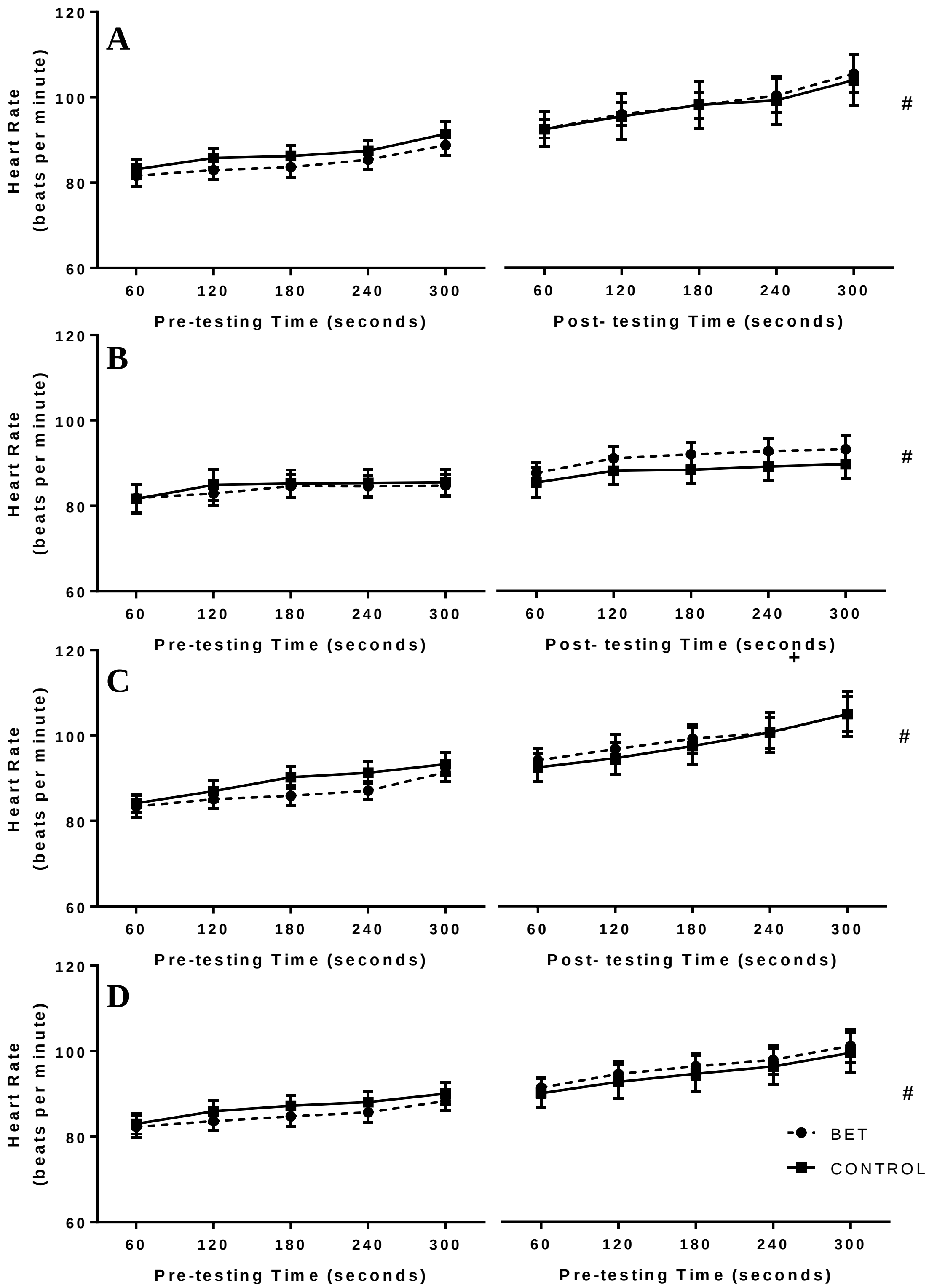


**Figure 5.14** Effect of brain endurance and physical training on heart rate during the subsequent (A), concurrent (B) and solo (C) tasks. # Significant ($p$<.001) main effect of time. Data presented as M ± SEM.

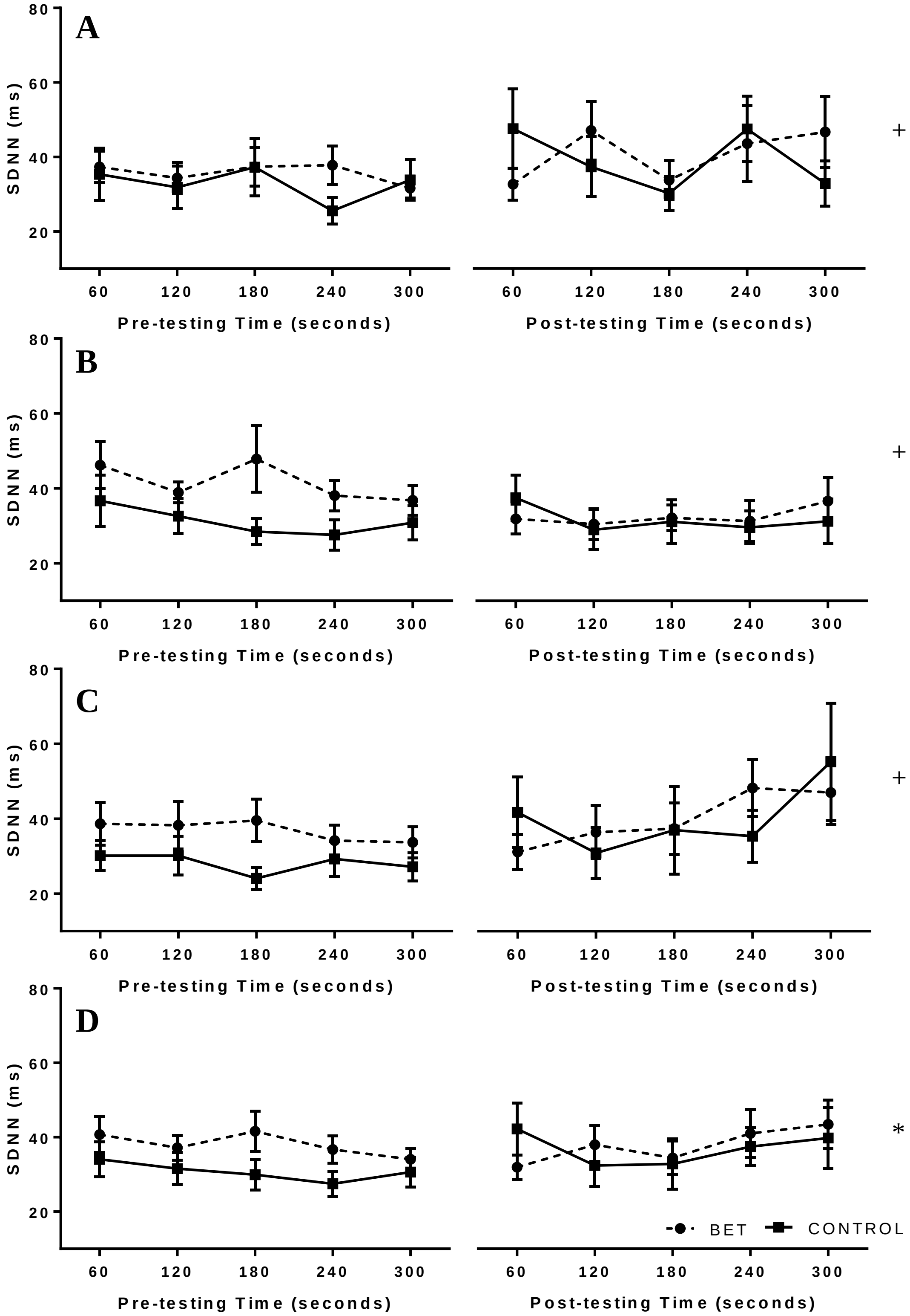


**Figure 5.15** Effect of brain endurance and physical training on heart rate variability (RMSSD) during the subsequent (A), concurrent (B) solo (C) and all (D) tasks. Significant ($p$<0.05) interaction effect of test-by-task (+) and test-by-time-by-group (*). Data presented as M ± SEM.

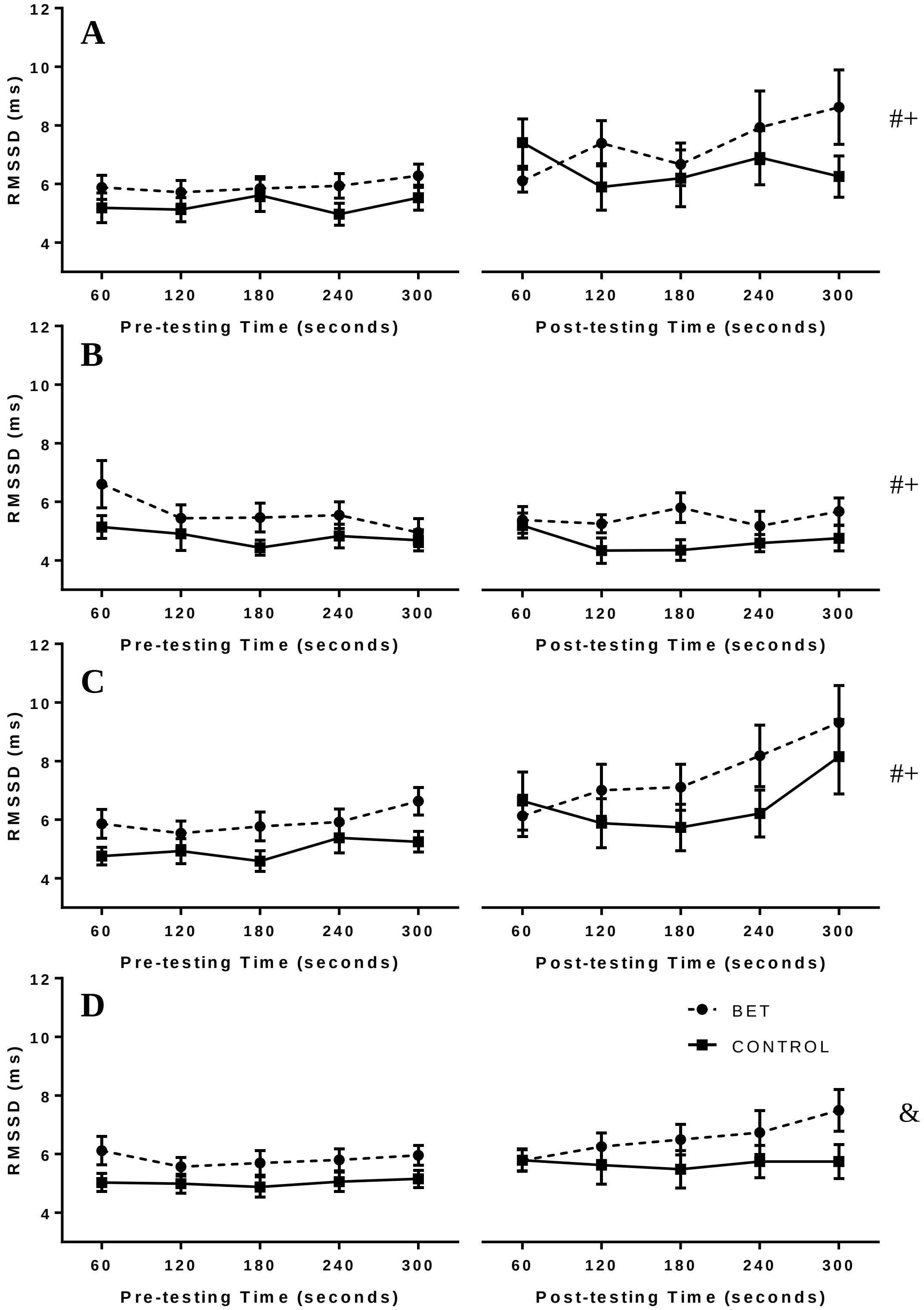


**Figure 5.16** Effect of brain endurance and physical training on heart rate variability (SDNN) during the subsequent (A), concurrent (B) solo (C) and all (D) tasks. Significant ($p$<.05) interaction effect of test-by-task (+), task-by-time (#) and test-by-time-by-group (&). Data presented as M ± SEM.

#### 5.4.4.2 Cognitive tasks

Cardiac measures for the cognitive component of the subsequent task was analysed with a group (2) by training (2) by time (10) mixed design ANOVA resulting in main effects for time only (figure 5.17) for HR ($F_{9.31}$ = 4.15, $p$<.001, $\eta^2$=0.11), RMSSD ($F_{9.31}$ = 2.37, $p$<.05, $\eta^2$=0.07) and SDNN ($F_{9.31}$ = 2.19, $p$<.05, $\eta^2$=0.06).

A series of 2 group (BET, Control) by 2 test (pre, post) by 20 time (30 s averages) ANOVAs were performed on the prefrontal FP2 cortical haemodynamic response measures (figure 5.18) for the cognitive component of the subsequent task yielding main effects for time on nTHI ($F_{19.646}$ = 7.618, $p$<.001, $\eta^2$=.0.183) and test on $O_2Hb$ ($F_{1,34}$ = 6.808, $p$<.05, $\eta^2$=.0.167). A further time by group interaction ($F_{19,34}$ = 1.831, $p$<.05, $\eta^2$=.051) was yielded for $O_2Hb$ and a test by time by group interaction ($F_{19.646}$ = 2.522 $p$<.001, $\eta^2$=.0.069) for HHb.

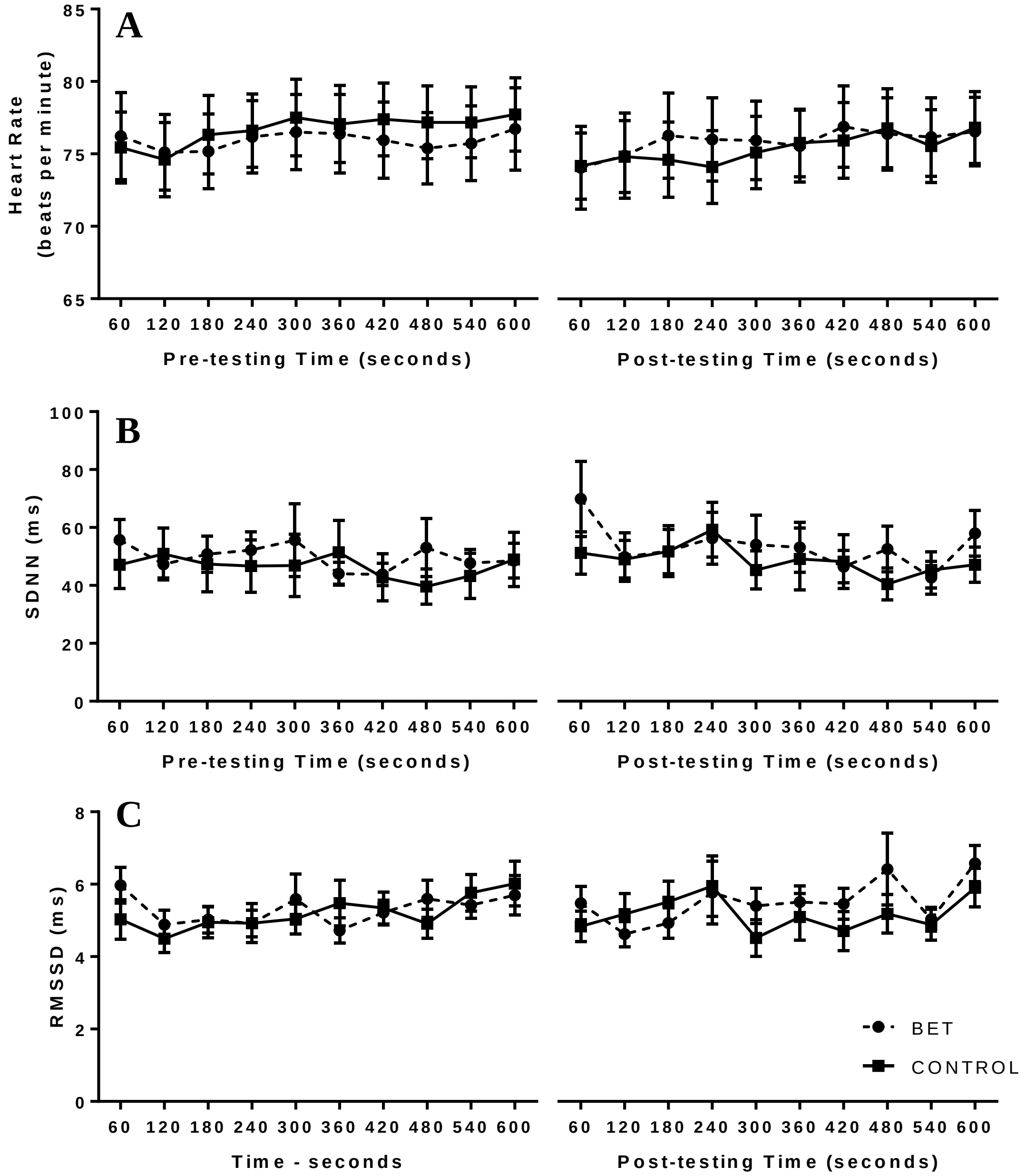


**Figure 5.17** Effect of brain endurance and physical training cardiac responses of heart rate (A) and measures of heart rate variability (B – RMSSD, C – SDNN) during the cognitive component of the subsequent task. # Significant ($p$<.05) main effect of time
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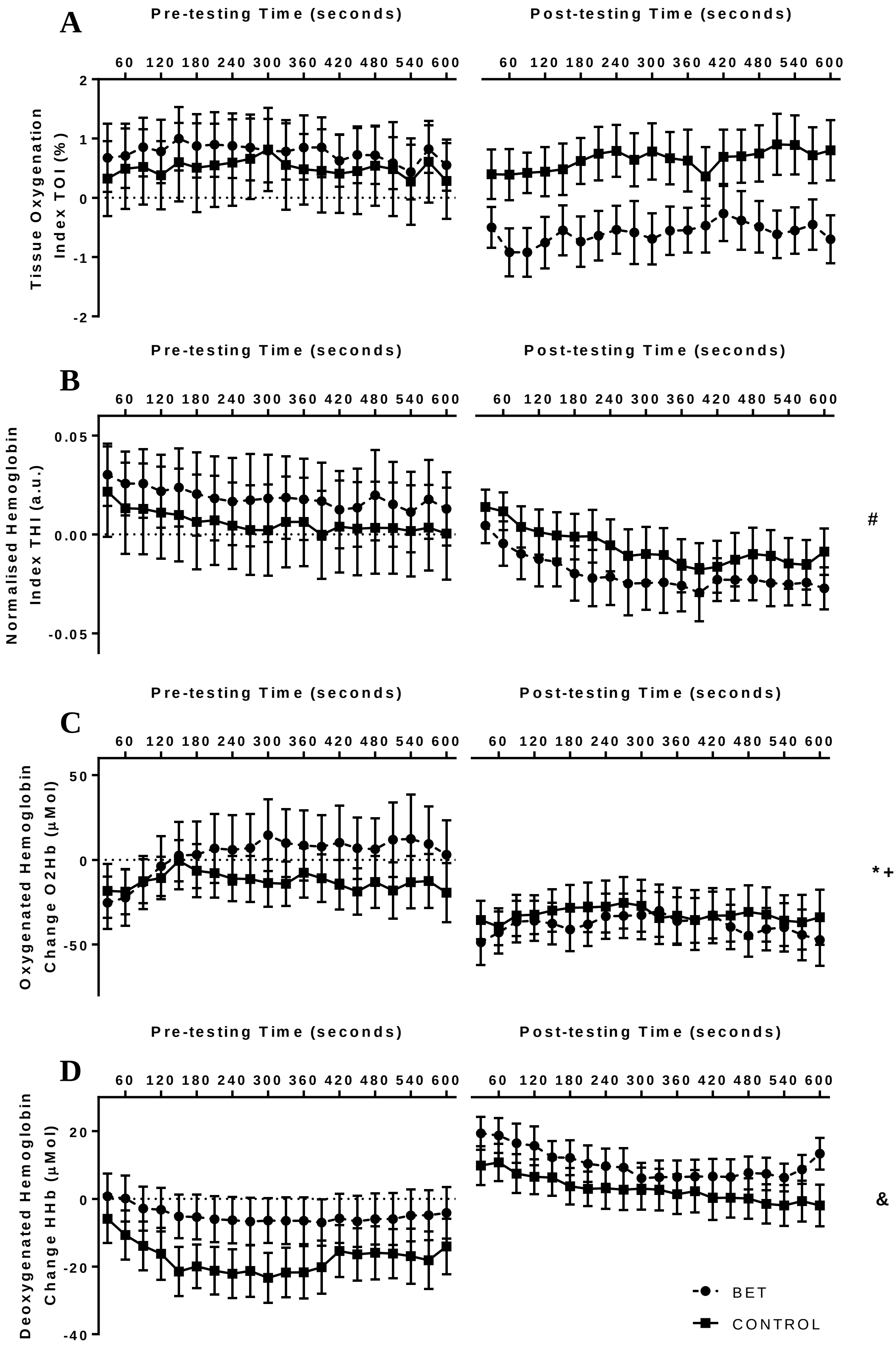


**Figure 5.18** Effect of brain endurance and physical training on prefrontal cortex activation (FP2) for TOI (A), THI (B), O2HB (C) and HHB (D) during the cognitive component of the subsequent task. # Significant main effect for time (*p*<.001) * Main effect test (*p*<.05). + Significant time-by-group interaction (*p*<.05). & Significant test-by-time-by-group interaction (*p*<.001).

## 5.5 Discussion

Our study was designed to evaluate the effects of concurrent BET on endurance performance and to examine underlying mechanisms. We demonstrated that 6-weeks of BET improved dynamic rhythmic handgrip performance over physical training alone and found evidence that changes in prefrontal cortical haemodynamics could mediate this effect.

Our findings of greater improvements in a physical performance following BET is consistent with the observations of Marcora [8], albeit ours represents a smaller improvement. The 32% overall task improvement (compared to 41% in Marcora's study at the 6-week test), could be due to the shorter cognitive task engagement during BET (60 versus 180 minutes per week), differing modes of endurance exercise (muscular endurance versus whole-body) and test type (time trial versus time to exhaustion). In contrast to Marcora's study we did not observe lower RPE in the BET group, relative to control, during post-training testing due to our use of a maximal, compared to a sub-maximal and fixed workload performance test. We also observed that both groups' increases in post-test performance were achieved with the same pacing strategy, RPE, and success motivation whereas task interest/enjoyment decreased more in the BET group than control group. In addition to an increase in physical performance, under all three testing conditions, we observed an increase in performance in the cognitive elements of the tests However, this did not transfer to a novel task, indicating that cognitive improvements from BET are task dependent.

### 5.5.1 Prefrontal Cortical Haemodynamics

Our secondary aim was to investigate potential mechanisms underlying the benefits of BET. The PFC consists of multiple interconnected areas that communicate with various subcortical structures in order to exert executive control, such as response inhibition, working memory and facilitate goal directed behaviour [37]. It has been suggested that during exercise the PFC interprets physiological information in combination with psychological factors, such as arousal and motivation, to facilitate a top-down effect on motor unit recruitment [38]. World-class endurance athletes are able to maintain cerebral oxygenation during 5-km running time trials [39], whereas well-trained recreational athletes exhibit declines in cerebral oxygenation [40]. Moreover, PFC oxygenation declines at the point of fatigue [41,42], particularly in chronic fatigue patients, suggesting that it impairs exercise tolerance [43]. Several studies have shown increases in PFC activity, indicated by reduced cerebral oxygenation, during exercise and a reduced physical and cognitive performance in a concurrent executive function cognitive task during 20 km of high intensity (~70% $VO_2$ peak) cycling, [44] and 9 minutes of cycling at 85% peak power [45]. In the current study, the post-training physical task improvements in the control group were associated with a decrease in right hemisphere PFC oxygenation (TOI), which did not occur in the BET group despite an even greater force production. It is possible that the increased cognitive workload during BET increased blood flow and resulted in subsequent neural adaptations within the PFC and other key cortical areas involved in exercise and cognitive processing. In support of this idea, the efficacy of cognitive tasks to induce such cerebral haemodynamic adaptations has been demonstrated during 12 weeks (~30 hours) of working memory training, which improved measures of intelligence and maintained oxygenation in the

PFC relative to an active control group [46]. Similarly, three months of endurance training has been shown to maintain cerebral oxygenation during submaximal exercise in an overweight population [47]. Therefore, it is possible that the concurrent physical and cognitive task used in the current study induced greater central adaptations, resulting in an ability to maintain a higher PFC oxygenation during the post-training physical tasks. This could enable the BET participants to tolerate higher levels of perceived exertion (at the same absolute work rate), maintain executive control and resist response inhibition during physical tasks, ultimately resulting in increased performance. Finally, one might expect an effort-related drop in PFC oxygenation during the physical performance tasks prior to training. However, due to the unfamiliar nature of dynamic handgrip exercise the participants may lack the ability or experience to exert maximal effort and perform well on this type of task, consequently PFC oxygenation was not compromised for these pre-training measures.

### 5.5.2 Limitations

First, whilst every effort was made to control for physical training between groups with regards to force production and task time, there were variations between participants resulting in different lengths of engagement in the cognitive tasks during BET. Second, whilst we have demonstrated the efficacy of BET, care must be taken when generalizing from a muscular endurance training protocol to whole-body endurance training.

### 5.5.3 Future Directions

Further investigations should aim to determine the optimal cognitive training volume during BET coupled with more detailed examination of the cortical adaptations using fMRI, EEG, and whole-brain fNIRS. Future research could be investigated in athlete's engaging in prolonged sub-maximal endurance exercise who are either time constrained or not able to replicate the physical demands of their competing event in training (i.e. ultra-endurance) as the addition of a concurrent cognitive task to their training programme may illicit further performance improvements

### 5.5.4 Conclusion

We have produced evidence that supports the efficacy of BET in improving muscular endurance performance and task specific cognitive ability, albeit at a cost of reduced interest and enjoyment. Physical performance improvements were associated with a training-induced maintenance of PFC oxygenation, which could reflect reduced mental effort during physical activity. This study shows that adding an additional concurrent mentally demanding stimulus to sub-maximal muscular endurance training requiring a high level of cognitive effort can improve muscular endurance performance over matched physical training alone

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6

# General discussion

The research presented in this thesis aimed to investigate the role of engagement in cognitive tasks on subsequent muscular endurance performance to address gaps in the literature regarding mental fatigue and ego depletion. Additionally, the concept of brain endurance training (BET) was investigated. This is a training strategy to place an additional mental demand during physical training to negate the negative effects of mental fatigue and improve performance.

The experiment presented in Chapter two demonstrated that response inhibition cognitive tasks of five and 20 minutes in length did not impair isometric handgrip exercise at 30% maximum voluntary contraction (MVC), but tasks of 10 minutes did. Learning effects were observed during the 20 minute response inhibition cognitive task. This adaptive response to prolonged engagement in a response inhibition task may account for a lack of physical performance decline following tasks of 20 minutes in length. The learning effects (indicated by an improved task performance) observed in the final five minutes of the 20 minute incongruent colour word task, suggest that the participants have adapted to the task and are no longer having to overcome inhibition in response to the visual stimuli. This would allow for at least five minutes from the participant having to exert response inhibition to completing the physical task. As brief periods of rest, in between completing an inhibiting depletion task and subsequent performance task, have been shown to attenuate the ego depletion effect, this may account for an improved physical performance over the briefer incongruent tasks.  The study utilised a triple task paradigm and it was demonstrated that completing a prior cognitive response inhibition task improved a novel cognitive response inhibition task completed several minutes later. There were no group differences in measures of intrinsic motivation for the three tasks, which would have led to similar task performance if the results were to be predicted from the motivational account of the ego depletion effect. Additionally, these results would not have been predicted by the strength control model and are better explained by cognitive control theory. There will be a need to allocate cognitive resources to overcome the response inhibition demands during the 10 minute incongruent cognitive task. When the participant switches to a physical outcome task, with no response inhibition, there will be a short latency period to reallocate the focus of their cognitive control away from response inhibition processes. As a result, physical performance is impaired. As previously stated, in the final five minutes of the 20 minute incongruent task response inhibition is no longer required. It is possible that five minutes of the incongruent task was not enough time to reallocate cognitive resources to manage the response inhibition demands and therefore had no impact on the following physical outcome task at 30% MVC. Additionally, further support is added to the cognitive control theory to explain these findings due to the improvements in cognitive performance observed throughout the sequence of consecutive tasks in the incongruent groups. These time on task performance improvements support the cognitive control theory, which predicts the allocation of attentional resources to the task at hand. These are likely to improve performance, rather than the strength control model, which predicts that performance should decrease due to a reduction in the global self-control resource.

The triple (possibly even greater than three) task paradigm should be employed more often in the examination of the ego depletion effect, specifically when investigating it in the context of physical activity. It provides an opportunity to use tasks from both the same and different domains giving further insight into the effects of domain task switching on the ego depletion effect. Performance should also be monitored throughout the manipulation and outcome tasks, so the ego depletion effect can be evaluated in relation to the development of mental fatigue, cognitive control theory as well as the strength control and motivational models. Both the strength control and motivational models were originally developed to explain the ego depletion effect in behavioural and lifestyle contexts rather than on exercise performance. However, when investigating the ego depletion effect on physical tasks, the cognitive control model can better account for the adaptation to task demands, which improve performance, and for a deterioration in performance when switching to a task in a different domain.

The findings presented in Chapter three demonstrated that engagement in a mentally demanding cognitive task, without response inhibition, for a period of 20 minutes did not impair isometric handgrip exercise at 30% MVC. These findings did not support the experimental hypothesis, which could be due to a lack of response inhibition in the cognitive task, or the task being too short in duration. A period of 20 minutes was chosen so the results could be compared with those in chapter two and provide further insight into the role of response inhibition within the cognitive task on impairing a subsequent submaximal isometric handgrip task. As there was no detriment in physical performance, relative to the control condition, this could not be determined. Further experimentation of a non-inhibition cognitive task (such as the 2-back used) of 10 minutes in length could help to answer this question. The results could be compared with the those found in chapter two where a response inhibition task of 10 minutes was found to impair physical performance. However, it is possible that a 2-back task of 10 minutes in length will not be of sufficient duration to induce a state of mental fatigue to impair performance and the results will be similar to the congruent colour word control task used in chapter two. If this were found to be the case, a 3-back or 4-back task could be employed to increase task difficulty.

However, even though there was no effect on physical performance the engagement in the 2-back test for a period of 20 minutes was enough to induce a state of mental fatigue and decrease prefrontal cortex (PFC) oxygenation. This may have resulted in an overcompensation effect (i.e. a hyperaemia response) during the physical task that maintained tissue saturation and therefore did not impair performance. This finding led to the idea of the concept of a cognitive warm up before physical performance tasks. Many sports require a high level of cognitive processing, to maintain a high level of effort and optimal pacing strategy alongside tactical considerations and completion of complicated motor control movement patterns in order to perform to the best of one's ability. Future research should investigate the use of a brief cognitive task to be included as a component of a mental warm up as any compensatory cerebral blood flow could potentially improve performance. Care would have to be taken to ensure that a state of mental fatigue was not induced, which could impair the subsequent physical performance. Additionally, brief cognitive tasks involving response inhibition should also be avoided to avoid the ego depletion effect.

In contrast to previous findings from Bray and colleagues in 2008, the increase in electromyography (EMG) activity, during submaximal isometric handgrip following engagement in a cognitive task, was not elevated. This could be due to the lack of a response inhibition requirement in the cognitive task. Similarly, they were not found in rhythmic self-paced muscular endurance exercise tasks utilised in the experiment presented in chapter four, following both non-response inhibition and response inhibition tasks. This experiment could be repeated with a response inhibition cognitive task to examine if elevated EMG readings during isometric exercise can be replicated.

Chapters two and three, both used a set-work load submaximal isometric handgrip exercise, whereas the experiments in chapters four and five utilised a self-paced rhythmic handgrip exercise. The isometric handgrip enabled a direct comparison to the previous work in the area of ego depletion, but the findings may not translate to whole body endurance exercise. The novel rhythmic handgrip exercise mode was chosen as it enabled further investigation into the role of an induced state of mental fatigue, both as a function of cognitive task and task duration, on sub-maximal self-paced muscular endurance. This mode of exercise enables multiple physiological measures to be taken in a practical and efficient manner. However, as highlighted in chapters four and five, even though these experiments have given further insights into the role of mental fatigue on muscular endurance exercise, and the efficacy of BET, care must be taken when generalizing findings to whole-body endurance and isometric muscular tasks.

The effects of a series of bouts of cognitive tasks, with and without response inhibition, on self-paced rhythmic handgrip exercise and physiological and psychological indices of mental fatigue were investigated in Chapter four. It was found that engaging in cognitive tasks, both with and without response inhibition, for a period of 10 minutes induces a state of mental fatigue as determined by measures of psychological self-report states and decreases in heart rate variability. Over time the psychological and physiological indices of mental fatigue diverge, with self-report measures accentuating and the physiological measures attenuating. After 20 minutes this state of mental fatigue will impair performance on a self-paced rhythmic muscular endurance task, but further bouts of cognitive task did not exacerbate the decline in performance. The duration of cognitive task engagement, independent of response inhibition, falls between the thresholds reported in the literature for isometric (a few minutes) and whole-body (half an hour) endurance exercise. Future research should investigate the impact of shorter cognitive task durations, and intermittent cognitive tasks, on whole-body endurance exercise. Additionally, as most of the previous research on the impact of mental fatigue on whole-body and isometric muscular endurance exercise performance has utilised response inhibition tasks, cognitive tasks without response inhibition should be further examined. The intermittent nature of this experiment, through the repeated blocks of cognitive task followed by a muscular endurance task, demonstrated that the physical activity alleviated the subjective state of mental fatigue induced by the cognitive tasks. This finding has implications for anyone who wishes to reinvigorate themselves from a mentally fatigued state and is supported by the vast amount of literature that has demonstrated improved cognitive performance following brief periods of exercise.

The data presented in chapter five could be examined with regression analyses to examine mediation and moderation effects to predict the variables responsible for the decline in muscular endurance performance. These results could then be interpreted in light of the motivational accounts of the ego depletion effect. As presented in the general introduction to this thesis, the motivational account of ego depletion proposes that performance declines are due to a shift in motivation from ‘have to’ to ‘want to’ goals. The motivational account of ego depletion also proposes that shifting motivational priorities can work in reverse. For example, once a person has completed desirable ‘want to' tasks, they may experience an increase in motivation for more demanding and laborious 'have to' tasks. During the repeated blocks of cognitive – physical tasks utilised in chapter five, ratings of interest and enjoyment (representative of intrinsic motivation) declined in the two cognitive task groups but was maintained in the control group. It is possible that the maintenance of interest and enjoyment throughout the experiment, in control participants, facilitated their higher physical performance rather than an increase in mental fatigue reported in the other two groups. If this were the case then future research could investigate if engaging in interesting and enjoyable tasks can improve performance in subsequent demanding physical and/or cognitive tasks, through satisfying the desire for 'want to' activities, as a form of 'ego replenishment' so that motivation increases in subsequent 'have to' activities.

The majority of previous research on mental fatigue and exercise performance has evaluated physical performance using either time trials or time to exhaustion tests. Within a sports science laboratory, most of these performance measures are conducted with the participants being blinded to how well they are doing during the actual physical task. For example, typically no power or speed data is provided during cycle time trials and no duration information is provided during time to exhaustion tests. This is not comparable to real world sporting events where athletes are usually aware of their performance in real-time and can pace themselves accordingly, notwithstanding any influence form other competitors and tactical considerations. Further experimentation should be conducted where performance feedback is provided to participants whilst they are in a state of mental fatigue to increase ecological validity. Since this thesis has been completed, pilot data from an experiment with similar methodology to the experiment conducted in chapter four has been completed by myself and colleagues, which has shown that when visual performance feedback is provided to mentally fatigued participants, in the form of percentage of MVC produced per second and total force accumulated, measures of extrinsic motivation are increased and muscular endurance performance is not impaired. Additionally, the performance feedback did not change the self-selected pacing strategy. This finding has real world implications to coaches, who should monitor their athletes state of mental fatigue on a day-to-day basis and provide them with further performance feedback if the athlete has deviated below their baseline values. Monitoring of an individual's state of mental fatigue could be implemented with simple category ratio 10 scales as used in the experiments presented in this thesis, or alternatively visual analogue scales. It may be possible to utilise short cognitive tasks and monitor fluctuations in performance to determine their state of mental fatigue on an acute and chronic level. In combination with typical physiological monitoring, which already occurs, this could inform the coach if the athlete is both mentally and physically prepared to engage in high quality and demanding training sessions on an acute basis. On a chronic level it will help the coach manage their athlete's accumulative physical and cognitive load and schedule periods of rest where appropriate. In a team sport setting this could also aid in team selection. These suggestions can form the basis for a whole new area of investigation.

The findings in chapter four demonstrated that performance in a dynamic rhythmic handgrip exercise is impaired when in a state of mental fatigue. As a result, it was suggested that this mode of exercise could be incorporated with mentally demanding cognitive tasks as a practical method of investigating the efficacy of BET and explore its underlying physiological mechanisms. This was undertaken in chapter five.

Chapter five investigated BET during a six week, (four sessions per week) rhythmic submaximal handgrip training protocol. Cognitive tasks, both with and without, response inhibition were used during training. Endurance performance improved by 32% in the BET participants relative to 12% in participants who completed the same physical training. Additionally, performance in a cognitive task utilised during the training period improved by 7% in the BET participants relative to 1% in the matched physical training group. However, these performance improvements did not transfer to a novel cognitive task, indicating that cognitive improvements from BET are task dependent. Increased performance in the BET participants occurred with a higher PFC oxygenation during the post-training physical tasks, over time, relative to control. It is possible that the concurrent physical and cognitive task used during BET can induce greater central adaptations, resulting in an ability to maintain a higher level of PFC oxygenation during the post-training physical tasks. This could enable the BET participants to tolerate higher levels of perceived exertion (at the same absolute work rate), maintain executive control and resist response inhibition during physical tasks, ultimately resulting in increased performance. It has been hypothesized that mental fatigue impairs physical performance via the anterior cingulate cortex (ACC) as it is activated by both exercise and complex cognitive tasks. It remains to be determined if physical and mental tasks that activate the ACC have overlapping or additive effects on performance. Further investigations should aim to determine the optimal cognitive training volume and type of cognitive tasks during BET coupled with more detailed examination of the cortical adaptations using fMRI, EEG, and whole-brain fNIRS. Further research could examine the differences in brain regional activity and multifactorial brain connectome approaches to the differences in elite athletes, trained and sedentary participants in response to exercise and mentally demanding cognitive tasks. This would enable the following questions to be investigated. Are there differences in an elite athlete's brain, which aid in their ability to tolerate high levels of exertion and discomfort during exercise? Is this a result of their training or genetic factors? What are the neuro-physiological determinants of mental fatigue and perceived exertion? These are all complex and interesting questions, which would be difficult to address.

The experiment presented in chapter five presented the concurrent method of BET where the cognitive stimulus is responded to during physical exercise. This can be achieved in a setting away from the laboratory, through computer based cognitive tasks or auditory applications on a smart phone where the athlete responds with a 2 button response whilst completing their training. Although the concurrent method of BET has proved to be effective at improving endurance performance, it may not always be possible for athletes to complete cognitive tasks during their physical training, especially in team sports or away from a controlled training environment (such as a gym). Alternatives to the concurrent method of BET are the 'pre-fatigue' and 'separate' methods. Since the completion of this thesis, colleagues and I have further investigated these methods with mixed results. The pre-fatigue method of BET proposes that engaging in mentally demanding cognitive tasks prior to physical training can induce a state of mental fatigue, increasing ratings of perceived exertion (RPE) during the subsequent physical training and improve endurance performance. This hypothesis was tested with similar methodology to the experiment in chapter five. Participants (randomized to a Control or BET group) completed five weeks training (20 sessions) comprising of submaximal hand contractions, once a second, until reaching a force target relative to their MVC. In addition, the BET group completed cognitive tasks (2-back, word incongruence Stroop) for 20 minutes prior to the physical training with similar results. In the post training physical tasks, handgrip endurance performance improved more following pre-fatigue BET (24.2%) than physical training alone (12.5%). The BET group showed higher prefrontal oxygenation at post-testing but the same RPE, motivation, cardiac and EMG activity compared to controls. The separate method of BET proposes that the cognitive tasks are completed separately to any physical training. This method has also been tested within our laboratory, with participants completing 20 sessions of the same BET cognitive tasks utilised in chapter five and self-paced rhythmic handgrip endurance exercise tasks used to access endurance performance. The BET group were more resilient to the post-testing cognitive tasks at inducing a state of mental fatigue but no improvements in physical performance were measured. If further investigations supplied evidence for the efficacy of the separate method of BET, it could be of interest to injured athletes who have an enforced reduction in the level of physical training they can complete. The separate BET method could also be investigated in injured participants only, as it could have benefits in aiding their overall mental state if they start to feel helpless, unmotivated and depressed due to not being able to physically train whilst injured.

Taken collectively, these initial investigations suggest that both the concurrent and pre-fatigue methods of BET could be an effective training strategy to increase resilience to mental fatigue, lower perception of effort during endurance tasks and, as a result, improve performance. The improvements observed in chapter five did come with reduced ratings of interest and enjoyment, so coaches and athletes should be cautious when employing these techniques. The majority of people engage in sport and physical training for fun, health and self-improvement and even though BET may improve performance ultimately it will be futile if people cease participation due to a lack of interest. In the era of 'marginal gains', where coaches are examining all aspects of their athlete's lifestyle, equipment and training methodology, BET may be of interest to professional athletes. However, coaches should still proceed with caution when using BET techniques with elite athletes as they are under a higher level of pressure and mental demand, and additional cognitive load could result in unintended negative consequences. As previously discussed, if coaches monitored their athletes' level of mental fatigue they would have more information to decide if BET could be applied to their training, in a periodized manner and away from high intensity training and competition. BET techniques could be beneficial for athletes engaging in prolonged sub-maximal endurance exercise who are either time constrained (for example, a high achieving executive who is highly motivated to achieve a personal best or beat a local rival), or not able to replicate the physical demands of their competing event in training (i.e. ultra-endurance) as the addition of a concurrent cognitive task to their training programme may illicit further performance improvements.

## Conclusion

To conclude, the findings from this thesis and the wider literature, along with my interpretations, are summarised in the list below:

1. Brief response inhibition cognitive tasks of approximately four minutes in length can impair isometric handgrip time to exhaustion at 50% MVC.
2. Brief response inhibition cognitive tasks of 10 minutes in length can impair isometric handgrip time to exhaustion at 30% and 50% MVC.

3. Moderate length cognitive tasks of 20 minutes, both with and without response inhibition, do not impair isometric handgrip time to exhaustion at 30% MVC.
4. Time on task learning effects can occur after 15 minutes of engagement in a cognitive task with response inhibition.
5. The increased EMG muscle activity observed during submaximal isometric contractions, following engagement in a cognitive task, is likely to require the process of response inhibition in that task.
6. Mental fatigue can be induced in cognitive tasks (both with and without response inhibition) of only 10 minutes in length as indicated by self-report and heart rate variability measures.
7. Indices of mental fatigue can diverge over time, with psychological self-reports increasing and physiological measures decreasing.
8. Cognitive tasks (both with and without response inhibition) of at least 10 minutes in length can induce a state of mental fatigue and impair self-paced rhythmic handgrip performance in tasks of five minutes in length.
9. Whole-body endurance exercise is impaired following 30 minutes of engagement in cognitive tasks with response inhibition.
10. Six weeks of BET, completed with cognitive tasks (both with and without response inhibition) can improve self-paced rhythmic handgrip, and task specific cognitive performance, which was associated with a higher PFC oxygenation relative to a matched physical only training group.