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## DOCTOR OF PHILOSOPHY

# The Role of Cognitive Challenges in Endurance Performance and Recovery

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# The Role of Cognitive Challenges in Endurance Performance and Recovery

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# SUMMARY

Previous studies have highlighted that certain cognitive challenges, such as mental fatigue and self-control, may interfere with endurance exercise performance. Although it has been acknowledged that psychological factors could be detrimental for post-exercise recovery, few studies have investigated the role of cognitive challenges in recovery from endurance exercise. Likewise, few investigations have focused on interventions that allow athletes to maintain exercise performance when they deal with external cognitive challenges. The present thesis consisted of four studies with two main aims. Firstly, it investigates mental fatigue in the context of post-exercise recovery. Secondly, it investigates the use of noninvasive brain stimulation (electroencephalogram, EEG, neurofeedback) after a cognitively challenging task to improve endurance exercise performance. The first experiment adopted a multidisciplinary approach to investigate the effect of mental fatigue induced via the performance of 40-min cognitive task on acute post-exercise recovery (90 min) following a 45-min strenuous cycling exercise. Participants completed three randomised laboratory visits, two of which started with the 45-min strenuous cycling task followed by either a 40-min cognitive task or a control condition during which participants viewed a 40-min documentary. In the third visit, participants completed the 40-min cognitive task with no prior 45-min cycling task. Subjective and neurophysiological measures (EEG) indicated that the 40-min cognitive task induced a state of mental fatigue. However, it did not influence the trajectory of the post-exercise recovery markers (e.g., heart rate variability and perceived recovery and cycling time-to-exhaustion test) when compared to the 40-min control documentary. The second study adopted an observational design to investigate the longitudinal effect of daily mental fatigue on perceived post-exercise recovery and morning fatigue and energy dimensions of mood. This time daily self-reported mental fatigue, post-exercise recovery state and mood state were assessed during the two weeks prior to an important race in a sample of 110 amateur endurance athletes. A hierarchical linear modelling approach was used to analyse these data. Results indicated that daily mental fatigue and training load were negatively associated with perceived daily post-exercise recovery after controlling for muscle soreness, baseline recovery state and fitness level. Daily mental fatigue and training load also predicted low morning mood state (high fatigue and low energy) after controlling for sleep quality. Despite the impact that mental fatigue may have on athlete’s ability to train and recover, few investigations have highlighted strategies that could counteract this detrimental effect. Hence, the third study consisted of a two-part experiment where participants completed a 12-min EEG-neurofeedback intervention to modify frontal hemispheric asymmetry after a cognitively demanding task. The effect of the intervention was tested on a cycling time-to-exhaustion test. The first part adopted a between-subject design consisting of three experimental groups, two of which received the neurofeedback interventions. The third group acts as a passive control group. The second part adopted a within-subject design. Results indicated that the neurofeedback intervention modified frontal hemispheric asymmetry ($p$=0.038) and the increased relative left frontal hemispheric activity neurofeedback significantly improved endurance performance (part A: $p$ =.050; part B: $p$=.028). The second study adopted a multidisciplinary approach to examine the mechanisms of this effect. This time, however, the effect of the intervention on hemispheric asymmetry was not as robust as in the previous study and yielded no significant effect on performance ($p$=.781). In light of this inconsistency suggestions for how to approach neurofeedback protocols are provided within the discussion of the thesis. Results of this thesis are discussed in relation to motivational processes of mental fatigue and the approach-avoidance motivation model of frontal hemispheric asymmetry.

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# DECLARATION

I hereby declare that this thesis is the results of my own investigations, except where otherwise stated.  All other sources are acknowledged by bibliographic references. This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree unless, as agreed by the University, for approved dual awards.

# CHAPTER 1

## GENERAL INTRODUCTION

The term *endurance performance* has been applied to exercises that require sustained physical effort for at least 60 seconds and often considerably longer (see Gastin, 2012; McCormick et al., 2015). In general, performance in endurance sport is characterized by the ability to sustain a given velocity or power for the longest possible time (Jones & Carter, 2000). Optimal performance in endurance sport develops from physiological adaptations to aerobic training. These adaptations are ultimately reflected in improvements of key physiological parameters, such as maximal oxygen consumption and exercise economy (Jones & Carter, 2000). To gain these adaptations, athletes consistently undergo intense training sessions, for instance recreational cyclists train on average 11 hours a week (see for example McCormick et al., 2018) with some cyclists reporting up to 20 hours a week.

Previous studies have highlighted that several psychological and cognitive factors can interfere with performance and training (McCormick et al., 2018; McCormick et al., 2015), for example it has been shown that mental fatigue (Marcora et al., 2009) and emotion suppression (Wagstaff et al., 2014) impair performance. Although some authors have acknowledged that psychological challenges could be detrimental also for post-exercise recovery (e.g., Kenttä et al., 2001, Piacentini & Meeusen 2015), few studies have investigated the cognitive challenges that may interfere with recovery from endurance exercise. Likewise, few investigations have focused on interventions that allow athletes to maintain the performance in the face of these cognitive challenges, especially when athletes have little time to rest. Nonetheless, an examination of these matters could be important for developing beneficial practices for endurance athletes.

Hence this thesis examines the effect of cognitive challenges on post-exercise recovery and also investigates EEG-neurofeedback as a brain-based intervention to maintain performance when facing cognitive challenges. Chapters 2, 4 and 5 adopted a multidisciplinary approach integrating neurophysiological (electroencephalogram, EEG), psychological (e.g., self-reported feelings, affective state and perception) and physiological (e.g., heart rate and heart rate variability) measures to comprehensively characterised the role of mental fatigue in the context of recovery and performance and how brain-based strategies could circumvent cognitive challenge prior to exercise performance.

This first chapter is organised as follows: the first paragraph provides the working definition of the cognitive challenges investigated in the thesis, namely mental fatigue and cognitive self-control, a brief summary of mental fatigue and self-control research in sport with an emphasis on endurance performance. The second paragraph presents the setting for Chapters 2 and 3 of the thesis by highlighting the intersection between mental fatigue and exercise-related fatigue. The last paragraph introduces neurofeedback and provides a summary of its application in sport. It then delineates the functional significance of frontal hemispheric asymmetry and how it has been integrated into the study of self-control and performance in Chapters 4 and 5 of this thesis.

## Cognitive Challenges

Cognitive activities require effort and could elicit a state of fatigue. In healthy individuals, fatigue is a common and time-limited feeling that arises from prolonged effort and disappears with appropriate rest (DeLuca, 2005). From a psychological perspective, fatigue has been defined as “the feeling that people may experience after or during a period of cognitive activity” (Boksem, & Tops, 2008). Accordingly, acute mental fatigue has been described as a multifaceted phenomenon that manifests with time-on-task at neurophysiological, psychological and behavioural levels. As such, it has been operationalised via the assessment of individuals psychobiological state during and/or after the performance of prolonged, standardised cognitive tasks. In particular, research has characterised mental fatigue as an increased subjective feeling of effort to perform the activity (see for example Hopstaken et al., 2015a, Hopstaken et al., 2015b; van der Linden, Frese, & Meijman, 2003). Mental fatigue is also experienced as lack of energy and reduced subjective level of arousal and alertness (e.g., Lorist et al., 2009; Schellekens et al., 2000; Trejo et al., 2015).

The subjective feelings of fatigue are often accompanied by behavioural and cognitive features. However, these behavioural outcomes could manifest later than subjective feeling due to compensatory effort (see Hockey, 2011). Previous studies reported impairment in cognitive control with higher cognitive functions being more sensitive to mental fatigue compared to automatic and learned processes (e.g., van der Linden, Frese, & Meijman, 2003; van der Linden, Frese, & Sonnentag, 2003); for instance, response time and the time necessary to plan and organise goal-directed strategies increase with time on task (van der Linden, Frese, & Meijman, 2003). Based on the neurophysiological signal (event-related potentials of electroencephalogram) and behavioural data it has been reported that fatigued individuals have a diminished tendency to monitor and correct errors (Boksem et al., 2006; Lorist et al., 2005), distinguish and make use of performance relevant information (Faber et al., 2012; Lorist, 2008; van der Linden & Eling, 2006), and inhibit task-irrelevant stimuli (Boksem et al., 2005; Hopstaken et al., 2016). Overall, the results suggested that fatigued individuals, even if still able to maintain basic cognitive processes, shifted from a goal-directed/proactive cognitive control to more automatic and stimulus-driven responses becoming less able to cope with/ adapt to unexpected events, and more susceptible to distraction.

The analysis of the electroencephalogram (EEG) signal confirms that mental fatigue is associated with reduced cognitive processing and is characterised by decreased arousal. For instance, investigations adopting EEG signal spectral analysis[1] consistently found increased

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[1] This technique decomposes the time-series signal into its frequency components to determine the strength of frequency-specific activity, i.e., power. The frequencies are grouped into four main bands (delta 0-3Hz, theta 4-8Hz, alpha 8-12, beta 13-25Hz). In general, the frequency band activity in a specific area of the brain provides information about neural and cognitive processes occurring during the recording.

power of theta band and lower alpha band as time-on-task advanced either across the scalp (Boksem et al., 2005; Lorist et al., 2009) or in the fronto-central areas (Barwick et al., 2012; Trejo et al., 2015; Wascher et al., 2014). In general, increased power in the low frequencies band occurs in the transition from an awakening, alert state to a drowsy and sleeping brain state (Klimesch, 1999). Alpha power in particular is associated with functional inhibition of neural activity (Klimesch et al., 2007) and tonically elevated spectral power in the lower part of the alpha frequency band (i.e., 8-10Hz) could reflect difficulties to maintain a state of alert wakefulness (Klimesch, 1999). Interestingly, Boksem et al. (2005) also found a significant positive correlation between low-alpha power and self-reported task-aversion. Similarly, the widespread increase in theta power during prolonged cognitive task is supposed to reflect decreased arousal and depressed cognitive processes when the individual is challenged after a period of sustained attention (Oken et al., 2006; Paus et al., 1997).

Moreover, it has been found that as the time-on-task increases individuals reported increased aversion to continuing with the present activity (Boksem et al., 2005; Faber et al., 2012) as well as reduced interest, engagement and motivation toward the activity (Gergelyfi et al., 2015; Hopstaken et al., 2015a; Möckel et al., 2015). These symptoms indicate that decrements in performance can be partly due to a motivational shift that occurs with the increasing time-on-task (see Hockley, 2011; Boksem & Tops, 2008). Consistently, investigations have implemented motivation manipulations (such as monetary incentives, social comparison) throughout the prolonged cognitive task and have reported that the manipulations reversed behavioural markers of mental fatigue (see for example Boksem et al., 2005; Lorist et al., 2009; Hopstaken et al., 2015b). Authors however reported that motivation did not account completely for the behavioural outcomes of time-on-task. Indeed, after the motivation manipulations participants had to select a strategy (i.e., increase response time or increase response accuracy) to restore their performance (Boksem et al., 2006; Hopstaken et al., 2015b; Lorist et al., 2009).

Overall, this acute state of mental fatigue could be defined as a “stop emotion” (van der Linden, 2011) that arises from a cost-benefit analysis of the ongoing activity when the activity is perceived as no longer beneficial (Boksem and Top, 2008; Hockley, 2011). In this framework, fatigue is an adaptive feeling and, although unpleasant, is necessary to promote energy conservation and the maintenance of appropriate and efficient behaviours. When demanding tasks are encountered over time, fatigue arises to favour the withdrawal from the task and motivate the individual to look for new opportunities or rest (Inzlicht et al., 2014; Inzlicht & Berkman, 2015; Kurzban et al., 2013).

It should be noted that some researchers have distinguished between traditional *mentally fatiguing tasks* and *self-control manipulations* (e.g., Van Cutsem et al., 2017) with the first referring to standardised cognitive tasks lasting longer than 30 min (such as the 2-Back task, the Stroop Colour Word Task, or Flanker task). On the other hand, self-control manipulations are often used in the stream of research referred to as “ego-depletion” (Baumeister & Vohs, 2007). In this research field, self-control is defined as the capacity of the individuals to override pre-potent or automatic responses to regulate the behaviour appropriately for the context and is considered a limited resource that can be “depleted” across tasks or over time (Baumeister & Vohs, 2007). Methodologically, the effect of a short self-control task (usually lasting less than 10 min) is studied in a sequential paradigm whereby this first depleting task is followed by a second short task used as probing test for the “depletion effect” (Baumeister et al., 2007). However, in recent years the limited-resource interpretation of “ego-depletion” effect has been challenged (e.g., Carter et al., 2015; Lurquin et al., 2016). Hence, researchers have proposed that self-control could be considered one of the different forms of self-regulation, which arises when opposite goals compete for a response (see Inzlicht et al., 2021; Werner & Milyavskaya, 2018). Namely, self-control entails a conflict between competing motives and is the processes through which the individual advance one motives over another. For example, a runner competing in a 10 km race has the goal to conclude the race in 40 minutes, however the discomfort that arises while exercising at times elicits the motives to slow down the pace. In this context, self-control should refer to the ability to endure the effort to pursue the runner primary goal. On the contrary, failure of self-control has been interpreted in terms of motivational shift. It should be noted that self-regulation could entail self-control (Fujita, 2011; Inzlicht et al., 2021). However, they are separate concepts with the first referring to the broader process that allows the individual to manage their goals (Fujita, 2011). Hence, it covers what goal to pursue, planning and implementing goal-pursuit. The present thesis mainly focuses on self-control.

From a methodological perspective, self-control manipulations usually consist of tasks similar to that used by traditional mental fatigue research, though they are shorter and are primary based on response inhibition (e.g., Stroop Colour Word task). Because the effortful nature of these self-control tasks and the similar characteristics to mental fatigue manipulations, some authors argued that the "ego-depletion" effect may be considered a form of short acute mental fatigue (Inzlicht et al., 2014; Inzlicht & Friese, 2019; Inzlicht & Schmeichel, 2012). Consequently, self-control manipulations could elicit the same symptoms and phenomenology described above for acute mental fatigue, e.g., fatigue, frustration, reduced task engagement (e.g., Lin et al., 2020). In general, the cognitive tasks used in mental fatigue and "ego-depletion" literature relies on mental effort and engage top-down cognitive control that refers to the brain processes necessary to organize and adapt goal-directed behaviours (Botvinick & Braver, 2015). These processes are reflected in the different domains of cognition, defined executive functions (i.e., flexibility, working memory, inhibition, planning and updating). However, Niendam and colleagues (2012) delineated that a common pattern of activation across these domains, the frontoparietal network which includes the prefrontal cortex; in particular the superior, middle and inferior frontal gyri, the anterior midcingulate cortex and superior parietal lobe. In addition, areas of premotor cortex, orbitofrontal cortex and subcortical structures, i.e., thalamus, caudate and putamen were found to activate across cognitive domains. The anterior cingulate cortex (ACC), in particular, is a key structure implicated in performance monitoring and flexible regulation of cognitive control processes (Botvinick & Braver, 2015). Thanks to the interconnections with other subcortical areas, the ACC is also involved in decision-making processes (e.g., Vassena et al., 2014). Hence, some authors argue that it represents a possible bridge between cognitive control processes and effort-based decision-making (e.g., Botvinick & Braver, 2015; Shenhav et al., 2013). Accordingly, when cognitive control processes are deployed over time (Boksem et al., 2006) or across tasks (Inzlicht & Gutsell, 2007), this monitoring system weakened.

Hence, although there are different interpretations around cognitive self-control and mental fatigue, researchers have agreed that motivational factors are involved in the exacerbation of their psychophysiological symptoms (see Kurzban et al., 2013 and commentaries for an extensive discussion on this topic). As proposed by the process model of self-control (Inzlicht et al., 2014), the aversive experience of mental effort reflects a motivational shift that guides attentional and emotional shifts, as such motivation, low arousal and inefficiency of cognitive control processes contribute together to the behavioural symptoms described above (Inzlicht et al., 2014).

Based on this view, the term *cognitive challenges* refers to demanding, effortful and continuous cognitive activities relying on top-down cognitive control. These cognitively demanding tasks may result in symptoms of fatigue, primarily subjective feelings which ultimately could have behavioural consequences. The manipulations implemented in the experimental chapters of the thesis were drawn from both mental fatigue literature and the "ego-depletion" literature.

### Cognitive Challenges and Endurance Performance

The above research investigated the effect of mental fatigue and cognitive self-control on cognitive performance, the interpretation, however, could also be relevant in the context of endurance performance. Indeed, the experience of fatigue arising from sustained cognitive effort and fatigue arising from sustained physical effort could share, at least in part, a common a neurobiological substrate. Boksem and Tops (2008) proposed that cognitive and physical effort could be guided and encoded by the same neural network because the human brain has developed in environmental conditions where the effort was primarily physical (i.e., hunting, fishing), while cognitive effort has become predominant later. Consistently with this view, research has shown that performing prolonged cognitive tasks prior to a physical endurance exercise can impair endurance performance (Marcora et al., 2009). This seminal study was replicated in different and independent laboratories (e.g., Brownsberger et al., 2013; MacMahon et al., 2014; Martin et al., 2016; Pageaux et al., 2014; Smith et al., 2015). In these studies participants performed in sequence an effortful cognitive task followed by an endurance test (see Van Cutsem for a review on this topic). This endurance test usually consists of a time-to-exhaustion test where individuals are asked to maintain the same exercise intensity for as long as possible (Marcora et al., 2009) or a self-paced exercise where individuals are required to complete a certain amount of work in the shortest time possible (e.g., run a certain distance mt as fast as possible, MacMahon et al., 2014; cover as much distance as possible in 20 min, Martin et al., 2016).  So far, a review (Van Cutsem et al., 2017) and a metanalysis have been published (McMorris et al., 2018) reporting that mental fatigue has a small negative effect on physical performance. Along with the effect on endurance performance, research consistently found that mental fatigue exacerbated perception of effort during the endurance exercise. The psychobiological model of endurance performance provides a theoretical framework to explain this spill-over effect of mental fatigue on endurance performance (Marcora, 2008; Marcora & Staiano, 2010). This model, based on the motivational intensity theory (Brehm, 1989), predicts that exercise termination occurs when the effort required to sustain the exercise reaches the maximal effort the individual is willing to exert to succeed in the task (potential motivation); or when the individual believes that continuation is impossible (Marcora, 2008). Accordingly, endurance performance should change (improves or decreases) relative to modifications in perceived effort during the task and/or potential motivation. However, few other psychological and neurophysiological variables have been investigated in the context of mental fatigue and endurance performance (Van Cutsem et al., 2017). Studies have reported no detrimental effect of mental effort on self-reported motivation to perform the endurance exercise (e.g., Marcora et al., 2009; Martin et al., 2016; Pageaux et al., 2014).

On a similar line, research on self-control reported that exerting self-control in short cognitive task, such as the incongruent Stroop Colour Word task, decreased persistence on a muscular endurance task compared to performing a control task, such as the congruent Stroop task (see, Bray et al., 2008; Brown & Bray, 2017; Graham & Bray, 2015; see also Englert, 2016 for a review). Interestingly, Graham & Bray (2015) reported that this detrimental effect of cognitive self-control on muscular endurance was mediated by lower task self-efficacy. Moreover, Brown and Bray (2017) reported that motivation manipulations (e.g., performance-contingent monetary incentives) reversed the detrimental effect of 12-min highly demanding cognitive task manipulation on a muscular endurance task. Though this effect was not related to a modification in self-reported motivation. Likewise, Brown and Bray (2018) showed that individuals after exerting self-control in a cognitively demanding task reported lower intentions to exert effort in a 30-min cycling endurance exercise along with lower total work performed in the actual cycling exercise. That is, the high demanding cognitive task reduced the participants' self-reported intended rating of perceived effort for the following cycling task. These results suggested that fatigued individuals experienced the exercise as more effortful, and a cost-benefit analysis of the task to be performed could, at least in part, account for this effect. Nonetheless, the neurophysiological and psychological mechanisms of this carry-over effect are largely unknown (Van Cutsem et al., 2017).

## Cognitive Challenges in Post-Exercise Recovery

Although fatigue and recovery are two separate concepts, they go together as fatigue is a state characterised by reduced functionality ultimately arising from sustaining prolonged period of work. Effective recovery, on the other hand, mitigates the accumulation of fatigue and prevents the symptoms of underperformance. Indeed, recovery can be described as the outcome state of several processes that occurs when the organism returns to its baseline activity level., i.e., when no demands (either physical or mental) are imposed on the systems (Geurts & Sonnetag, 2006; Rattray et al., 2015).

In general, intense endurance exercise is a stressor for the organism which has to mobilise resources to accommodate the exercise demands (Angeli et al., 2004; Hackney, 2006). The allostatic model proposes that the brain plays a central role in the stress-response by anticipating the needs and orchestrating the response to different internal and external challenges (McEwen & Gianaros, 2001; Sterling, 2011). Hence, allostasis reflects an active process through which the organism responds appropriately to different challenges. Importantly, in this model, individuals' experience and perceptions of the situation mediate the stress-responses and are used to coordinate the activity of the physiological systems (defined *allostatic systems*) implicated in these responses (McEwen & Gianaros, 2001; Sterling, 2011). Among the allostatic systems, there are the hypothalamus-pituitary axis, HPA, and the sympathetic and parasympathetic branches of the autonomic nervous system (Thayer & Sternberg, 2006). These physiological systems allow mobilising individual resources, such as increased heart rate and blood pressure, in response to internal and external circumstances. The activation of the HPA and autonomic nervous system in response to everyday challenges should be temporarily limited and elicit favourable adaptations. There are however situations that generate *allostatic load*. Namely, a chronic dysregulation of the allostatic systems which become hyperactive or hypoactive with detrimental consequences for the ability of the organism to adapt and function (McEwen & Gianaros, 2001). Allostatic load could be elicited by repeated exposure to external stressors that burden the same response, the failure to habituate to repetitive exposure of the same stressors and prolonged exposure to stressor due to lack of recovery (McEwen & Gianaros, 2001).

Based on this model, it is plausible that the external cognitive challenges one may encounter after exercise can interfere with post-exercise recovery. For example, cognitive challenges, one may encounter after training, could impose *wear* and *tear* on the allostatic system, like the autonomic nervous system, or by altering perception of recovery. In support of this notion, it was shown that life event' stress and perceived chronic stress significantly moderated the acute recovery (1 hour recovery) of maximal isometric strength after a resistance training exercise (Stults-Kolehmainen & Bartholomew, 2012).  These results were confirmed by the investigation of Ruuska and colleagues (2012) who reported a negative association between self-reported mental stress and the physiological adaptations to aerobic training routine (Ruuska et al., 2012). Due to the relationship with the rating of perceived effort during exercise performance, mental fatigue arising from sustained cognitive activities could represent an external challenge that influences athletes' perceptions, affective state and autonomic nervous system response after the exercise. There are several occasions where athletes could face mental fatigue after exercise. For instance, amateur athletes after performing their training sessions may deal with their occupational work or military personnel may have strategical meetings after intense physical training.  In these situations, mental fatigue could augment the strain induced with physical training. This is particularly important to address since lack of recovery is associated with performance decrements (Halson et al., 2002), mood disturbances (Kenttä et al., 2006), illness (Peake et al., 2017) and in general inadequate recovery could lead to overtraining syndrome (Meeusen et al., 2006).

Whole-body endurance exercise stimulates several body systems e.g., cardiovascular, respiratory and locomotor systems (Barnett, 2006). The time necessary to recover depends on the extent of the stimulus received, namely the intensity and duration of the training session and is heterogeneous across different body systems (Barnett, 2006). Research generally distinguishes three time periods to facilitate the study of post-exercise recovery (Bishop et al., 2008). Immediate recovery happens between bouts within the same exercise; short-term recovery extends from 10 min to 48 hours after the exercise; long-term recovery or macro-recovery involves several consecutive days or weeks. This long-term recovery represents the balance between the disturbances and restoration imposed by consecutive training sessions (see Bishop et al., 2008; Sluiter et al., 2000). Post-exercise recovery thereby has been investigated via the assessment over short- or long-time of different markers that are affected by the exercise. For instance, research in endurance performance have used physiological variables, such as heart rate recovery (HR), heart rate variability (HRV) (e.g., Stanley et al., 2013) and blood lactate level (e.g., DePauw et al., 2011), psychological variables, such as mood state (e.g., Hassmén & Blomstrand, 1991; Kenttä et al., 2006) or perception of recovery (e.g., Laurent et al., 2011), and behavioural variables, namely performance (e.g., DePauw et al., 2011; Meeusen et al., 2004) or response time and accuracy in cognitive tests (e.g., Decroix et al., 2016) to study acute post-exercise recovery and training-recovery balance.

In particular, the dynamics of heart rate recovery and heart rate variability (HRV) after endurance exercise have been extensively investigated because they provide information about acute responses and long-term adaptations of the cardiocirculatory system and autonomic nervous system to aerobic exercise (Bellenger, et al., 2016; Plews et al., 2013; Stanley et al., 2013). In brief, heart rate variability, HRV, is a measure of fluctuations of RR interval (time period between consecutive heartbeats, also defined as heart period). The variability around RR intervals mirrors the modulation of the sympathetic and parasympathetic nerves directed to the sinoatrial node (Task Force, 1996). As such, HRV is adopted as an index of the autonomic nervous system's (ANS) influence on the heart period. Heart period variances can be decomposed into defined frequency components (spectral-domain methods) or can be summarised with statistical methods (time-domain methods), such as the square root of the mean squared successive heart period differences (RMSSD). The heart period variability reflects the respiratory sinus arrhythmia (RSA) that is the influence of the breathing pattern on the heart period as mediated by the vagal tone (Berntson, et al., 1997; Berntson et al., 2016). Although the respiratory rhythm influences both branches of the ANS, the action of the sympathetic system on the sinoatrial node has greater latency compared to the parasympathetic system as such it filters out the respiratory rhythmic fluctuations (Berntson et al., 2016). Consequently, measures of HRV are generally considered measures of parasympathetic gating into heart period. Among HRV measures, the high-frequency band of the spectrogram (0.15-0.4Hz) and the RMSSD are the more common markers of heart rate variability associated with vagal (i.e., parasympathetic) activity (Laborde et al., 2017; Task Force, 1996).

During exercise, heart rate increases, and heart rate variability decrease as a consequence of a complex interplay between the activity of the sympathetic and parasympathetic systems (see White & Raven 2014). When the exercise terminates, the HR and HRV gradually return to baseline values with an early and fast decline depending on the removal of the motor command and the reduction of arterial baroreflex that leads to an increased parasympathetic drive to the sinoatrial node (Michael et al., 2016). However, the complete restoration of the cardiac parasympathetic modulation could take up to 48 hours after exercise termination. Consequently, complete recovery of HRV could occur within 90 min for low intensity exercise up to 72 hours for long and strenuous exercise (Stanley et al., 2013). Different systemic responses elicited with the exercise contribute to the slow phase of parasympathetic recovery, for example the dynamics of the blood pressure after exercise, the accumulation of metabolites that activates the sympathetic system via metaboreflex response, the increased level of systemic catecholamine and others factors like the thermoregulation and blood flow redistribution (Stanley et al., 2013). For this reason, HRV is considered a standard marker of post-exercise cardiovascular and autonomic recovery (Stanley et al., 2013).

Cognitive tasks also involve the modulation of parasympathetic and sympathetic systems. Research has found a reduction in heart rate variability during demanding cognitive tasks (e.g., Fairclough & Houston, 2004; Hynynen et al., 2008). Importantly, it has also been reported that the time spent on cognitive tasks affects heart rate variability by reducing the RMSSD (Melo et al., 2017) or high-frequency power (Tran et al., 2009). Researchers have proposed that the prefrontal cortex plays a crucial role in maintaining the balance between sympathetic and parasympathetic activity via a bidirectional communication with the central nucleus of the amygdala and other subcortical regions (Thayer et al., 2009). Among other influences, the prefrontal cortex exerts an inhibitory (GABAergic) activity on the central nuclei of the amygdala (Thayer et al., 2009). Consequently, it has been suggested that reduced prefrontal cortex activation, as a consequence of engaging in prolonged cognitive activities, could result in decreased parasympathetic drive (Melo et al., 2019). As such sustained cognitive activities after intense exercise could delay parasympathetic reactivation. As mentioned above, allostatic load on this physiological system could result in autonomic dysfunction (e.g., hyperactivation or hypoactivation).

In accordance with the pattern of post-exercise heart rate variability, it has been reported that energetic arousal increased, and tension decreased immediately after a maximal incremental endurance exercise (Hall, et al, 2002; Hall et al., 2007, Hall et al., 2010). However, both returned to baseline level within 10 min after the exercise (Hall et al., 2007). Although moderate exercise may elicit positive mood (assessed with the profile of mood state, POMS e.g., Lane & Crone-Grant, 2002; see Berger & Motl, 2000 for a review), intense exercise and long-term assessment of mood revealed that strenuous training sessions and intensified training routines could elicit mood disturbances as assessed with the fatigue and vigour items of the POMS (Comotto et al., 2015; Kentta et al., 2006; ten Haaf et al., 2017). Some studies showed that the mood changes included also increased anxiety and depression, i.e., total mood disturbance (e.g., ten Haaf et al., 2017). Moreover, such mood disturbances may be alleviated with nutritional strategies (e.g., Killer et al., 2017) suggesting that practices athletes undertake during post-exercise could be important for the balance between positive and negative mood responses to the exercise. Hence, mood state and perception of recovery may be dampened when mental effort follows an intense endurance exercise.

To conclude, the matching symptoms of fatigue arising from endurance exercise and sustained cognitive activities suggest that mental fatigue after intense exercise could over-tax the organism and result in inadequate recovery. No investigation however has studied the effect of mental fatigue in the context of post-exercise recovery. This perspective could be equally important for identifying which practices potentially interfere with training-induced fatigue and decrease recovery processes, for developing strategies to prevent the accumulation of fatigue and for understanding the psychological commonalities between fatigue arising from sustained mental and physical effort.

## Recovery from Cognitive Challenges

The continuous alternation between occupational work and training sessions calls for research on interventions that restore performance to pre-fatigue level. Indeed, fatigue incurring through working day could increase perception of effort during the training and in turn, reduce the ability to maintain the required exercise intensity (e.g., Marcora et al., 2009) However, few investigations have focused on countermeasures to these cognitive challenges (e.g., Brown & Bray, 2017; Azevedo et al., 2016). As described above, Brown and Bray (2017) used monetary incentives to improve muscular endurance after participants underwent a12-min cognitive task manipulations. Although their results provide promising evidence to advance the understanding of the carry-over effect of mental effort, external reward such as monetary incentives may have little application in the context of daily training routine. Azevedo et al. (2016) instead investigated the ergogenic effect of caffeine in a mentally fatigued state and reported that caffeine could improve performance and vigour compared to the non-caffeine condition. Although the authors did not find statistical difference in performance between caffeine and placebo, they reported a possible benefit of caffeine via magnitude-based inferences (Hopkins et al., 2009). Furthermore, the amount of caffeine administered in this study (i.e., 5 mg p/kg) could have side effects and, if consumed consistently, could lead to withdrawal symptoms (e.g., Nehlig, 1999). In this context, recovery strategies should target the psychological challenges experienced by the athletes. Accordingly, Kenttä and Hassmén (1998) suggested that recovery strategies should match the symptoms, for instance if athletes experience cognitive over-stress, this should be treated with interventions that target this symptom. On a similar line, Rattray and colleagues (2015) suggested that brain-based intervention could foster the recovery from mental fatigue symptoms. Noninvasive brain stimulation, such as neurofeedback, could restore performance to pre-fatigue level and may be particularly relevant when athletes have little or no time to rest between occupational-related activities and physical training sessions. However, investigations on this topic remained limited (see Rattray et al., 2015) and no previous investigations have implemented noninvasive brain stimulation yet.

EEG-neurofeedback is a form of biofeedback whereby the individual receives meaningful feedback (i.e., sensory stimuli) about a physiological function of the body, in this case, cortical brain activity. When an individual becomes aware of his/her brain activity, he/she can recognize how to control and regulate it in the same way as watching his/her own movement in a mirror permits the modification and correction of form/posture. The mechanism behind self-regulation of cortical activity is, at least in part, related to operant conditioning (Sitaram, et al., 2017). Contingent feedback acts as reinforcements that allow users to heighten desired brain patterns and suppress undesired brain responses (see Sitaram et al., 2017). In this way, individuals learn to self-regulate brain activity when positive reinforcements, which acts as rewarding stimuli, are provided to correct/desired brain responses.

In practice, EEG-neurofeedback consists of a real-time EEG signal recording from which the relevant feature (e.g., a specific frequency band such as high alpha power) is extracted online. The computer software converts this target feature into meaningful and instantaneous stimuli that are displayed to the performer. The stimulus can take different forms, for example an auditory stimulus, e.g., a tone that changes in pitch (e.g., high to low pitch) or a visual stimulus displayed on the computer screen (such as histogram that changes in colour), or a blend of sensory stimuli. The stimuli constitute the reinforcement that provides the performer with continuous and instantaneous information about the recorded frequency band with respect to its desired/correct level. This desired level is usually established based on individual baseline power of the target frequency band (see Cooke et al., 2018; Enriquez-Geppert et al., 2017 for a methodological tutorial of EEG-neurofeedback).

The target frequency band and the desired level of activity within this frequency are the criteria of the neurofeedback training. Because the control over neural activity should ultimately induce behavioural, cognitive or affective changes (Gruzelier, 2014; Hammond, 2011), authors have highlighted the importance of establishing a valid and relevant criterion for the neurofeedback session (Cooke et al., 2018; Mirifar et al., 2017). In particular, Cooke and colleagues distinguish between two approaches to determine the rationale for the neurofeedback training, the data-driven approach and the prescription approach (Cooke et al., 2018).

The first approach is based on direct observation of the cortical activity associated with the behavioural or cognitive outcome. In this case, the neurofeedback training is specific and differs depending on the context of application (e.g., type of sport). This approach finds relevance in self-paced sport (e.g., golf, archery, shooting) where brain patterns underlying the successful performance can be observed and manipulated during the movement (see for example Ring et al., 2015). In the second approach, *prescription approach*, the neurofeedback criterion is indicated by theoretical evidence about the functional significance of the frequency band. That is, the researcher builds the neurofeedback session based on the knowledge around a specific frequency and infers possible behavioural, affective or cognitive effects (Cooke et al., 2018). In this way the neurofeedback training is less specific and could be applied across athletes and contexts. In adopting the prescription approach the researcher can also circumvent the recording of the EEG signal during the behaviour. For this reason, the prescription approach could be particularly relevant for sports where the direct observation of the neural determinants for performance are limited, such as whole-body endurance events. It should be noted that both approaches are driven by scientific evidence.

Neurofeedback has been used in clinical settings for several years (see Hammond, 2007; Hammond, 2011) and more recently has also been introduced in sport setting (see Cooke et al., 2018; Mirifar et al., 2017). In this context, EEG-neurofeedback has been applied in self-paced sport, such as archery and golf (see for example Cheng et al., 2015; Ring et al., 2015); on the contrary, it has never been applied in endurance performance. As suggested above, the prescription approach to EEG-neurofeedback advocated by Cooke et al. (2018) could be particularly useful to introduce this intervention in endurance performance. The paragraphs below explain the theoretical model that guides the application of EEG-neurofeedback in the context of endurance performance and cognitive challenges.

### *Frontal Hemispheric Asymmetry*

Investigations on brain frontal asymmetric activity originate from the clinical reports following unilateral brain lesions (Davidson, 1992). Such reports indicated that lesions to the left hemisphere were associated with depressive symptoms whereas patients with lesions to the right hemisphere were more likely to develop mania (Davidson, 1992). Over the years, research developed EEG metrics to study the functional significance of frontal hemispheric asymmetry (Allen et al., 2004; Smith et al., 2017). Because alpha power is associated with inhibited cortical activity, investigators use alpha power as an inverse indicator of frontal hemispheric cortical activity. Specifically, a single score, *frontal alpha asymmetry,* is commonly used to identify frontal hemispheric asymmetry and is computed by subtracting alpha power of the left leads from alpha power of the right homologous lead (e.g., alpha power F4- alpha power F3) (Allen et al., 2004; Smith et al., 2017). When frontal hemispheric activity is symmetrical, alpha asymmetry is equal to zero; positive numbers of alpha asymmetry reflect grater left over right frontal cortical activity; negative numbers indicate right over left frontal cortical activity (see Allen et al., 2004; Smith et al., 2017 for methodological reviews on the topic).

On the basis of the clinical reports, researchers proposed motivational and emotional models of frontal hemispheric asymmetry (Coan & Allen, 2004; Davidson, 1992; Harmon-Jones, 2003; Harmon-Jones & Gable, 2018; Reznik & Allen, 2017). According to the approach-withdrawal motivation model of frontal hemispheric asymmetry (Davidson, 1992; Harmon-Jones & Gable, 2018) relative left frontal cortical activity reflects a motivational system that drives the tendencies to approach and engage a stimulus (Davidson, 1992; Harmon-Jones &

Gable, 2018). On the other hand, relative right frontal cortical activity reflects withdrawal and avoidance-oriented actions (Davidson, 1992; Harmon-Jones & Gable, 2018).

From a theoretical perspective, approach and avoidance processes produce different tendencies, affects, motor and cognitive responses. Elliot and Thrash (2001) integrated approach and avoidance motivation in the achievement goals model as the valence dimensions of goal. In this framework, approach and avoidance processes provide the impetus (energization) for behaviour. Approach motivation entails thriving, the processes that move toward the desired end-state (Elliot, 2006). Hence, approach-oriented processes are commonly elicited with positive and/or rewarding stimuli. Avoidance motivation instead is about surviving by getting away from something potentially harmful stimuli (Elliot, 2006). Tendencies to avoid are more common in response to negative and aversive stimuli. The authors suggested that approach and avoidance orientations constitute the valence dimensions of goals achievement. That is, an achievement goal may be driven by approach processes, e.g., reaching a desirable possibility or avoidance processes, e.g., avoid undesirable possibility (Elliot & Thrash, 2001).

Harmon-Jones et al. (2013) instead focused the definition of approach-avoidance motivations on the direction of motivation independently from external factors (e.g., environmental stimuli or goals) (Harmon-Jones et al., 2013; Harmon-Jones & Gable, 2018). In particular, the authors suggested that approach-withdrawal motivations arise from internal processes at the trait and state level (see Harmon-Jones & Gable, 2018). According to the authors, individuals may be motivated to approach or avoid based on the expected end-state or external reward/punishment, yet these anticipations are not always at the basis of the motivation orientations (e.g., Coan et al., 2001). In this framework, motivation has been described as the internal state of an organism reflected in the energy that the organism will invest (see Brehm & Self, 1989). This internal state is characterised by a direction, namely where the organism is motivated to go. Approach motivation hence reflects the urge to move toward and withdrawal motivation the urge to move away (Harmon-Jones et al., 2013). In the context of asymmetric frontal cortical activity, high (intensity) approach motivation should be reflected by greater relative left over right frontal cortical activity. The present thesis centres on this definition of approach and withdrawal motivation because of its focus on the neurophysiological basis in terms of lateralization in frontal cortical activity.

Along with the motivational orientation, frontal hemispheric asymmetry has been studied in the context of emotional processes (see, Davidson & Irwin, 1999). Accordingly, left-sided frontal asymmetry is usually associated with positively valanced emotional responses and right-sided asymmetry is usually found in negatively valanced emotional responses (e.g., Wheeler et al., 1993). However, because left-sided frontal asymmetric activation has been associated with trait and state anger (e.g., Harmon-Jones & Allen, 1998) and is found also in response to non-emotionally salient stimuli (e.g., Rodrigues et al., 2018) the motivation orientation accounts of frontal asymmetry could be more appropriate to accommodate the range of findings on frontal hemispheric asymmetry rather than valence per se (Harmon-Jones, 2003; Spielberg et al., 2008). Nonetheless positively valanced emotions (e.g., happiness, interest) are more commonly found in approach-oriented processes and negatively valanced emotions (e.g., fear, disgust, anxiety) are more common in withdrawal oriented-processes (Davidson & Irwin, 1999).

In general, frontal hemispheric asymmetry has been studied as a trait-like measure as well as a state-dependent outcome. Researchers have reported an association between baseline hemispheric frontal cortical asymmetry and individual motivational and affective predispositions, i.e., behavioural activation and inhibition systems as assessed with Craver and White's (1994) BAS/BIS trait scale or measures of sociability and shyness (see Coan & Allen, 2004). Specifically, individuals with greater left over right frontal cortical activity also reported greater (self-reported) BAS trait which measures individual sensitivity to signals of reward and positive affective responses (e.g., Coan & Allen 2003; Harmon-Jones & Allen, 1997). This finding suggests that the approach system reflected in left-sided frontal asymmetry and the BAS scales may tap the same motivational system. In contrast, the association between right-sided frontal asymmetry and the BIS scale, which reflects predisposition to behavioural inhibition and increased attention and arousal, received less supported (Coan & Allen, 2003; Harmon-Jones & Allen, 1997). This suggests that the withdrawal system reflected by right-sided frontal asymmetry taps only partially the behavioural inhibition system described with the BIS scale. The capability model of frontal hemispheric asymmetry by Coan and colleagues (2006) expands these interpretations and proposes that individual differences in hemispheric frontal asymmetry are best captured during challenging situations rather than at "rest". These individual differences in asymmetrical frontal activity reflect individual abilities to respond with approach-/withdrawal affective style within specific situations (Coan et al., 2006; Coan et al., 2001).

In addition to the trait measures, frontal hemispheric asymmetry has been associated with affective and motivational states. Kelley et al. (2017) reviewed several methodological approaches that directly manipulate frontal hemispheric asymmetry to test the causal relationship between hemispheric asymmetry and behavioural and affective responses. Among these methods, the authors highlight the use of EEG-neurofeedback to manipulate frontal alpha asymmetry. Allen and colleagues (2001) were the first to use EEG-neurofeedback to modify frontal alpha asymmetry and tested the effect of this manipulation on self-reported and physiological responses to emotional eliciting video clips. The authors trained 18 women with a neurofeedback intervention to modify frontal alpha asymmetry (i.e., alpha power recorded from F4 and F3). Eight women were trained to increase alpha asymmetry score (increase relative right alpha power) which indicates greater left-over right frontal cortical activity. The other group was trained to decrease alpha asymmetry score (increase relative left alpha power) which indicates greater right over left frontal cortical activity. The training consisted of five 6-min neurofeedback sessions (i.e., 30 min) for five consecutive days. Before and after the training participants reported their rest affective state, moreover emotional responses to happy, sad, and neutral video clips were recorded. The neurofeedback intervention successfully modified frontal alpha asymmetry, with the increasing left training group reporting greater alpha asymmetry scores, while the increasing right group reporting lower alpha asymmetry scores. Importantly, following the increasing alpha asymmetry intervention, individuals reported more amusement, interest, and happiness relative to the happy video clip. Besides, the decreasing alpha asymmetry intervention resulted in less zygomatic muscular activity ("smile face") while the increasing alpha asymmetry intervention produced less corrugator activity ("frown face"). This neurofeedback intervention has been successfully replicated by other researchers (e.g., Harmon-Jones et al., 2008; Mennella et al., 2017; Quaedflieg et al., 2016; Peeters et al., 2014). Despite some differences in the neurofeedback protocols adopted, the neurofeedback interventions had a medium to large effect size on frontal alpha asymmetry across the studies. Moreover, the studies investigated behavioural and emotional outcomes of the training. Mennella et al. (2017) reported less baseline self-reported negative affect and anxiety following the increasing alpha asymmetry neurofeedback training. Harmon-Jones et al. (2008) tested the neurofeedback in the context of the cognitive dissonance model and found that increasing relative left cortical activity neurofeedback reduced cognitive discrepancy. That is participants rated their previous choices more positively and the rejected choices more negatively. On the basis of these results, the authors suggest that relative left cortical activity is implicated in action-oriented cognitive processes. Altogether these studies confirmed that neurofeedback training can be used to manipulate frontal alpha asymmetry and this manipulation mediates approach-/withdrawal-oriented behaviours and emotions.

To summarise, in this paragraph it has been shown that frontal hemispheric asymmetry reflects two neural circuits associated with approach and withdrawal orientations. The *approach system* supports appetitive behaviours (i.e., goal-directed actions and cognitions) and instantiates approach-related emotions, such as anger, enthusiasm, interest. In contrast, the *withdrawal system* facilitates departure from aversive stimuli and generates withdrawal-related emotions such as fear, anxiety, disgust (Davidson & Irwin, 1999). Importantly the relative activation of this system can be externally manipulated and elicits approach-/withdrawal-oriented processes.

## Cognitive Challenges and Frontal Hemispheric Asymmetry

As previously highlighted, cognitively demanding tasks may induce a motivational and goals priorities shift. The findings summarized above would suggest that frontal hemispheric asymmetry could be relevant in this context.

On one hand cognitively demanding tasks could elicit approach-/avoidance processes. For instance, Schmeichel and colleagues (2015) found that individuals with greater self-reported BAS (i.e., behavioural activation system) displayed greater left over right frontal hemispheric asymmetry in response to positive pictures viewing after a cognitive “depleting” task (Schmeichel et al., 2015). The authors suggested that exerting self-control could increase the propensity to approach pleasant outcomes. However, the study focused on emotional responses to a task that did not imply any effort. In contrast, everyday tasks could entail effort such as engaging in highly demanding tasks, and the experience of negative valence, delivering a public presentation despite feeling anxious. Even if these tasks could feel unpleasant at times, they lead to desirable outcomes or states and could be beneficial in the long-term. In the context of cognitive challenges and endurance performance, approach-related processes may serve as a way to (re-)evaluate the physical effort when the individual had dealt with cognitively demanding challenges. That is, if the aversive feelings arising from engaging in cognitively demanding tasks decrease (/increase) the value (/the cost) of performing further demanding activities (e.g., Gieseler et al., 2020; see also Kurzban et al., 2013), approach/withdrawal processes could be important to behaviours following cognitive challenges. Accordingly, research based on neuroimaging techniques showed that activation of the left dorsolateral prefrontal cortex is associated with behavioural approach independently from the valence of the stimulus received and thus may be implicated in energizing behaviours for successful goal-pursuit when self-control is required (Berkman & Lieberman 2010; Spielberg et al., 2012). Based on this, it plausible that the network instantiating approach-orientated processes could overlap in part with the processes implicated with effort evaluation. However, approach-/withdrawal-motivation has received little attention in research on mental fatigue / cognitive self-control and exercise performance.

## The Present Experimental Chapters

The previous paragraphs have highlighted some outstanding questions around cognitive challenges and endurance performance: Does mental fatigue influence post-exercise recovery from endurance exercise? Can EEG-neurofeedback be used to circumvent the negative effect of cognitive challenges on performance? Does frontal hemispheric asymmetry (approach-/withdrawal motivation) influence the behavioural effects of these cognitive challenges?

The experimental chapters in this thesis aimed to answer these three questions. The studies in Chapter 2 and Chapter 3 investigated the effect of mental fatigue on post-exercise recovery by adopting an experimental approach in a laboratory-based setting and an observational approach in a field-based setting, respectively. The studies presented in Chapter 4 and Chapter 5 examined the effect of EEG-neurofeedback to modify frontal hemispheric asymmetry on endurance performance after a cognitively demanding task. Furthermore, three laboratory studies (Chapter 2, 4 and 5) adopted a psychophysiological approach aiming at understanding some underlying mechanisms of cognitive challenges and endurance performance relationship.

Specifically, the experiment presented in Chapter 2 added a new layer of insight to the areas post-exercise recovery and mental fatigue by establishing whether physiological and psychological markers of acute post-exercise recovery are disrupted when mental fatigue is induced within the period that immediately follows demanding physical activity. The study adopted a multidisciplinary approach by including physiological (heart rate variability, EEG) self-reported perceptual (recovery and perception of effort), psychological (mood and affective state) and performance (cycling time-to-exhaustion test) markers. It was hypothesised that a prolonged cognitive task placed immediately after a 45-min intense cycling task would impair the recovery trajectories of these markers during a 90-min recovery period compared to a control condition that used a passive activity (i.e., watching documentary) in place of the cognitive task and a further control condition that completed the cognitive task but no prior 45-min cycling task. It was also hypothesized that performance on a time-to-exhaustion test (TTE) immediately following the 90-min recovery period would be worsened by the combined effect of exercise and cognitive tasks compared to the control conditions.

Built on the findings of Chapter 2, the study reported in Chapter 3 adopted a longitudinal approach to investigate the relationship between mental fatigue and post-exercise recovery in a “real world” setting. This setting consisted of an amateur cycling race in Italy with approximately 9000 entrants taking part each year. This longitudinal approach circumvents the acute arousing effect of exercise on the self-reported variables recorded (i.e., perception of recovery and mood state). This design also determined whether mental fatigue would affect post-exercise recovery over more a chronic period. Importantly, this is a novel approach within the stream of research on mental fatigue and sport performance and provides an ecologically valid setting to investigate mental fatigue. Athletes were monitored throughout the two weeks preceding the event with self-reported measures of post-training recovery and morning mood state (fatigue and vigour). Hierarchical linear modelling was used to determine the relative contribution of mental fatigue and training load to self-reported measures of recovery prior to this endurance event.

The two experimental studies presented in Chapter 4 and 5 were the first to investigate the use of EEG-neurofeedback to modify frontal hemispheric asymmetry in the context of endurance performance and a cognitively demanding task. In particular, Chapter 4 included a two-part experiment; the first consisted of a between-subject design, while in the second part the same group of participants was tested in a fully repeated measures design. Forty participants were divided into three experimental groups, two of which received a 12-min neurofeedback intervention designed to either increase or decrease frontal alpha asymmetry. The third group serves as a passive control group to test the effect of neurofeedback over and above a period of passive rest. Prior to the neurofeedback, participants engaged in an effortful, depleting cognitive task. After this cognitive task participants received the neurofeedback or the control intervention following which they underwent a cycling endurance performance test. The test consisted of a cycling time-to-exhaustion and perception of effort (i.e., RPE) was recorded throughout this test. The alpha asymmetry scores during the intervention, rating of perceived effort during the cycling test and performance of the three groups were compared. This same experimental protocol was then tested in a within-subject design where the two neurofeedback interventions were compared.

Built on the previous chapter, the fifth chapter of the thesis aimed at replicating the effect of this same EEG-neurofeedback intervention on endurance performance and examining more in depth the mechanisms behind the effect of this intervention. To these aims, the study used a within-subject design that had the larger effect on frontal hemispheric asymmetry. A multidisciplinary assessment of mental fatigue was implemented before and after the mentally fatiguing task which preceded the EEG-neurofeedback intervention and the cycling time-to-exhaustion test. The effects of the EEG-neurofeedback interventions on affective responses and attentional control during the cycling time-to-exhaustion test were also examined.

### Thesis Format

Chapters 2 - 5 of the thesis consisted of three psychophysiological study in a laboratory setting and one observational study conducted in the field. All four chapters were written as stand-alone research papers. As such all manuscripts presented are independent yet linked and for this reason, at times there is an overlap between chapters. The numbering of figures and tables were restarted at the beginning of each chapter. To facilitate reading, abbreviations were defined on their first appearance within each chapter. Chapter 6 summarises the main findings of the thesis and aims to analyse these in relation to the literature, recognising the limitations and suggesting areas for future research. A single reference list is presented at the end of the thesis.

# CHAPTER 2

## POST-EXERCISE RECOVERY AND MENTAL FATIGUE: EXPERIMENTAL STUDY

## Abstract

**Objective**. This study adopted a multidisciplinary approach to investigate the effect of mental fatigue induced by the performance of prolonged cognitive task on short-term post-exercise recovery. It was hypothesized that mental fatigue negatively affected psychological and physiological markers of post-exercise recovery and athletes' ability to perform. **Methods**.

18 participants underwent three separate laboratory visits in a within-subject design. In two visits participants completed a 45-min intense cycling task followed by a 90-min recovery period during which they either performed a 40-min cognitive task (EX+COG) or watched a 40-min documentary (EX+DOC). In the third visit, participants only completed the 40-min cognitive task (COG). In each visit, at the end of the 90-min recovery period, performance was assessed with a final cycling time-to-exhaustion test (TTE). Psychological, (mood state, affective state) physiological (heart rate variability and cortical activity) and behavioural (response time and exercise performance) markers of recovery and mental fatigue were assessed throughout the 90-min recovery period. **Results**. The cognitive task alone induced a state of mental fatigue characterised by increased frontal theta power and subjective fatigue. However, the psychophysiological markers of recovery were not different between the EX+COG and the EX+DOC conditions, though the final TTE was greatest in the COG condition. **Conclusion**. This finding indicates that mental fatigue did not influence acute short-term recovery when compared to a control documentary. Any adverse effects of cognitive activity on exercise recovery are small and may only be detectable in the absence of prior physical activity. A similar state of low psychological and neurophysiological activation underlies fatigue induced with either strenuous exercise or sustained cognitive activity.

## Introduction

During the acute recovery period following intense endurance exercise, several biological (e.g., elevated heart rate), psychological (e.g., increased feelings of fatigue), and behavioural (e.g., performance) disturbances are observed. Ahead of subsequent exercise these disturbances should be attenuated so as individuals are not at risk of compromised performance and/or adaptation (Meeusen et al., 2012). Accordingly, the practices that one adopts during this acute recovery period are critical, with effective recovery practices helping to lessen such disturbances before the next bout of exercise, and ineffective practices potentially exacerbating them (for example, De Pauw et al., 2011).

Traditionally, physical or nutritional interventions have been used to alleviate exercise related disturbances during recovery. Examples include cryotherapy (Hohenauer et al., 2015), compression (Hill et al., 2014), and carbohydrate refeeding (Betts & Williams, 2010). Recently though, the psychological and cerebral connotations of disturbed recovery have gained more hypothetical interest (Rattray et al., 2015). Correspondingly, a small number of investigations have documented ways in which cognitive practices may be used immediately after endurance exercise to support post-exercise recovery (e.g., Pelka et al., 2017). While a focus on cognitive ways to support effective recovery is helpful, this focus has diverted attention away from other types of post-exercise cognitive practices that could disrupt recovery (e.g., Cook & Crewther, 2014; Crewther & Cook, 2012). An understanding of the factors that impair recovery is equally important in helping athletes and practitioners recognize how to optimize their recovery practices. This is especially important when one considers that individuals regularly encounter acute cognitive challenges after endurance exercise in many contexts. Examples of such contexts include tactical de-briefings and/or media commitments for athletes, the execution of unpredictable routines in military personnel, and the performance of vocational tasks in recreational exercisers. Some evidence suggests that psychological stress adversely influences recovery from resistance exercise for up to 96 hours (Stults-Kolehmainen & Bartholomew, 2012). However, there is a paucity of research investigating whether acute recovery is disrupted when challenging cognitive practices follow intense endurance exercise.

The lack of research focusing on the effects of cognitive practice during recovery from endurance exercise is surprising because many biological, psychological, and behavioural markers that are disrupted at the end of intense endurance exercise are also independently disrupted by cognitive activity. For instance, after intense endurance exercise, cardiac parasympathetic activity can be suppressed for up to 48 hours as indicated by reduced heart rate variability (HRV) (Stanley et al., 2013). Likewise, sustained cognitive activity has been found to independently reduce cardiac parasympathetic activity, especially when participants faced highly demanding cognitive tasks (e.g., Fairclough et al., 2005; Melo et al., 2017). In particular, the root mean square of the successive differences between RR intervals (RMSSD), a measure of parasympathetic modulation on cardiac activity (Laborde et al., 2017), is used to delineate post-exercise parasympathetic reactivation (e.g., Stanley et al., 2014) as well as parasympathetic modulation during cognitive task (e.g., Hansen et al., 2003; Melo et al., 2017).

Besides, sustained cognitive activity evokes feeling of fatigue (van der Linden et al., 2003) and impairs other psychological and perceptual markers such as energetic arousal (Lorist et al., 2009), perceived task competence (Gergelyfi et al., 2015) and the willingness to expend effort (van der Linden et al., 2003). This increased feeling of fatigue during prolonged cognitive activity is reflected in changes of electroencephalographic (EEG) activity (Craig et al., 2012), particularly in the theta (4-7 Hz) band, where theta power has a positive relation with fatigue (e.g., Washer et al., 2014). Self-reported fatigue and vigour, as well as readiness and motivation to train, are similarly altered in the short-term period that follows intense exercise (e.g., Termine et al., 2006; ten Haaf et al., 2017; Stanley et al., 2012). Hence, taken collectively, when intense endurance exercise is immediately followed by a sustained cognitive activity, it is plausible that acute disturbances to these recovery markers are greater due to the combined challenge that is encountered.

## Mental Fatigue and Endurance Performance

Mentally fatiguing cognitive tasks provide a dependable paradigm to investigate whether post-exercise recovery is acutely worsened when endurance exercise is followed by sustained cognitive activity. This is because sustained mental fatigue before endurance exercise is already known to compromise endurance performance (Marcora et al., 2009; Van Cutsem, Marcora et al., 2017). Hence, an empirical behavioural (Marcora et al., 2009), perceptual (Marcora et al, 2009), and psychophysiological (Brownsberger et al., 2013) link exists between these two separate modalities. Though a recent study by Vrijkotte et al (2017) has reported that mental fatigue in-between two bouts of incremental exercise did not affect exercise performance during the second incremental bout, it is possible that individuals reach the same level of subsequent performance in a worse biological or psychological state. However, the effect of mental fatigue in-between two exercise bouts on physiological markers like HRV, EEG, and psychological or perceptual markers such as mood, motivation and perceived recovery, is not known. The long-term effects of such compounded recovery could be far reaching given that individuals who recovery poorly are at greater risk of overtraining (Kellman et al, 2010), and that cognitive stress is hypothesised to play a part in consequences such as this (Kentta & Hassmen, 1998).

## The Present Study

This study aimed to add a new layer of insight to the areas post-exercise recovery and mental fatigue by establishing whether physiological and psychological markers of acute post-exercise recovery are disrupted when mental fatigue is inserted into the period that immediately follows demanding physical activity. We defined acute post-exercise recovery as the changes over a short-time period of physiological (RMSSD), cortical (EEG), perceptual (perceived recovery and perception of effort), psychological (mood and affective state) and performance (cycling time-to-exhaustion test) markers. With this in mind, we hypothesized that a 40-min cognitive task placed immediately after a 45-min cycling task (EX+COG) would lower RMSSD during a 90-min recovery period compared to a control condition that included a 40-min documentary watching in place of the cognitive task (EX+DOC), and a further control condition where participants completed a 40-min cognitive task but no prior 45-min cycling task (COG). It was also hypothesised that performance on a time-to-exhaustion test (TTE) immediately following the 90-min recovery period would be worse in EX+COG compared to EX+DOC and COG. We hypothesized that participants would experience lower self-reported mood state, affective state and reduced subjective experience of recovery when the 45-min cycling task followed by the 40-min cognitive task was compared to the other conditions. Lastly, we examined the combined effect of exercise and prolonged cognitive tasks on the power spectrum derived from the EEG signal and we expected that EX+COG condition would yield the highest levels of EEG theta-band power and would promote more threat-like cognitive appraisal.

## Methods

### Participants

A total of 21 participants (18 males, 3 females) were recruited from local cycling and triathlon clubs. Two participants did not complete the study due to injury, and one participant was excluded from the final analysis because he failed to complete one of the experimental treatments. Eighteen participants (2 females, 16 males) were therefore included in the final analysis [mean (*SD*); age 37.5 (8.6) years, weight 78.2 (7.9) kg, height 178 (8) cm, $\dot{V}O_2$ max 52.3 (11.6) $ml \cdot kg \cdot min^{-1}$, peak power output (PPO) 367 (48) W]. On average participants performed 8.17 (2.82) h of aerobic training per week and had been involved in cycling or triathlon for 4.36 (2.71) years. According to the guidelines developed by De Pauw et al. (2013) our participants conformed with the category performance level 2, i.e., trained recreational cyclists. The study received local University Ethics Committee approval for testing human participants. Before taking part, participants provided written informed consent but remained naïve to the aim of the study until they were fully debriefed at the end of the final visit. Before starting the experimental procedures, all participants confirmed that they were injury-free, were not taking any medication and did not have known neurological, cardiovascular, or respiratory diseases.

### Study Design and Procedures

Participants visited the laboratory on four occasions, the first of which was a preliminary visit to establish their maximal oxygen consumption ($\dot{V}O_2$max) and PPO. The remaining three visits were experimental visits and utilised a randomised, Latin Square design. In one experimental visit (EX+COG) participants first completed a continuous 45-min cycling task, that was followed by a 40-min cognitive task, and then a cycling time-to-exhaustion (TTE) test. The other two experimental visits were control visits. In one control visit, the 40-min cognitive task was replaced by a standard documentary (40-min) before the TTE test (EX+DOC). In the other control visit participants did not complete the 45-min cycling task and did complete the 40-min cognitive task before the TTE test (COG).

**Preliminary Visit.** In the first visit, participants performed a maximal incremental ramp test on a cycle ergometer to establish $\dot{V}O_2$max and PPO. The maximal incremental ramp test started with 2-min rest after which the power automatically increased by 25 W every minute until volitional exhaustion. Exhaustion was defined as the point at which the participant voluntary stopped pedalling, or cadence fell below 60 rpm for more than five consecutive seconds. The maximal incremental ramp test was performed on a Lode Excalibur cycle ergometer (Lode Excalibur Sport, Groningen, the Netherland) that was set in a hyperbolic mode. This allows the cadence to change independently from power output. During the maximal incremental ramp test, heart rate (HR) was recorded continuously via a remote transmitter (RS800CX, Polar, Kempele, Finland) and rating of perceived effort (RPE) was recorded every minute using the Borg CR-10 Scale (Borg, 1998). Oxygen uptake was measured breath by breath throughout the maximal incremental ramp test via a computerised metabolic gas analyser (Metalyzer® 3B, Cortex, Leipzig, Germany) with $\dot{V}O_2$max defined as the highest 30-s average at any time point. Before the maximal incremental ramp test, frame specifications on the cycle ergometer were adjusted according to participants' preferences and recorded for the ensuing experimental visits. Following this ramp test, participants were also familiarised with the cognitive tasks that were employed during the experimental visits.

**Experimental Visits.** Figure 1 provides a depiction of the experimental procedures for the three conditions. In EX+COG condition and EX+DOC condition, upon their arrival participants completed the Brunel Mood Scale (BRUMS), the short version of the Positive and Negative Affect Schedule (PANAS) and a single-item questionnaire about their motivation toward the 45-cycling task (see *Psychological Measures*). After this, they were fitted with the equipment for the EEG and HRV recording (see *Physiological Measures*). Then, they underwent 5 min baseline recordings of EEG signal and heart rate (RR data for heart rate variability analysis, HRV) while performing an Erikson Flanker task (see *Physiological Measures*). Following this 5-min period, participants completed the continuous 45-min cycling task. The continuous 45-min cycling task began with a 15-min block of cycling at a constant intensity of 45% PPO. After this the constant block, the intensity automatically increased to 65% PPO for a further 20-min block. The 45-min cycling task concluded with a 10-min time-trial (TT) during which participants were instructed to cover as much distance as possible. During this cycling task, the cycle ergometer was set to hyperbolic mode for the 45% PPO and 65% PPO blocks of constant intensity exercise. This ensured that cadence was free to vary independently of the constant intensity. For the ensuing 10-min TT, the cycle ergometer was set to linear mode. This linear setting was standardized to ensure that participants were cycling at 70% PPO when their cadence was anchored to a preferred revolution per minute (rpm) that was selected for each participant during the preliminary visit. This preferred rpm ranged between 75 and 100 rpm and was retained for the subsequent continuous cycling task for each cyclist. Cadence was free to vary during linear mode, hence, increasing cadence produced a corresponding increase in power output during the 10-min TT, and decreasing cadence produced a corresponding decrease in power output. RPE was recorded every 2 min throughout the 45-min cycling task and at the end of the last minute of the 10-min TT. HR was measured continuously and then averaged every 2 min for the analyses. A measure of blood lactate was obtained 3 min after the 45-min cycling task had concluded. After the 45-min cycling task, participants completed the same psychological questionnaires as earlier along with resource-demand evaluation questions and the motivation scale for the cycling TTE test (see *Psychological Measures*).

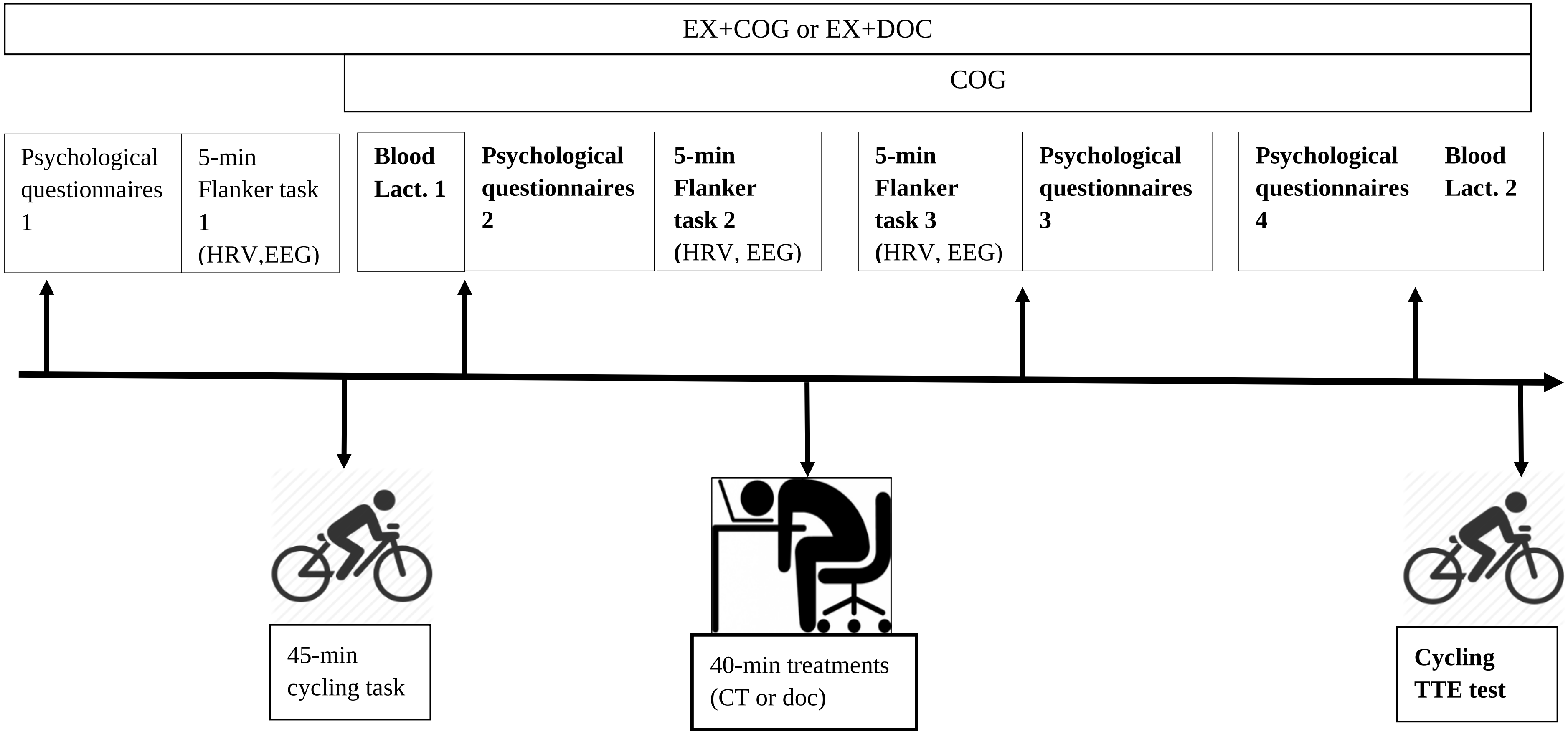
The COG condition started at this point with participants providing a resting measure of blood lactate and completing these same psychological questionnaires for the first time. During their COG condition, participants completed the same experimental procedures as EX+COG and EX+DOC thereafter. On completion of the psychological questionnaires, EEG and HRV were obtained from all participants as they simultaneously completed the same 5-min Flanker task as earlier. The 5-min Flanker task was then followed by a 40-min cognitive task for participants allocated to EX+COG and COG, while in EX+DOC they watched a 40-min documentary. Measures of EEG and HRV were recorded continuously throughout the 40-min cognitive task and the 40-min documentary. To prepare the EEG montage approximately 20 min elapsed between completion of the psychological questionnaires that followed the 45-min cycling task, and the start of the 5-min Flanker task followed by the treatments. After the 40-min cognitive task or the 40-min documentary, participants completed the same psychological questionnaires as earlier. At this point in all three conditions participants also completed the NASA Task Load Index (NASA-TLX) and the rating scale of mental effort (RSME) as well as the rating of their perceived recovery state (PRS; Laurent et al., 2011). After this, EEG and HRV were recorded again during the same 5-min Flanker task as earlier. Then, participants were permitted five minutes before undergoing the cycling TTE test. Immediately before the TTE test, all participants completed again the BRUMS, PANAS, resource-demand evaluation questions, motivation scale and PRS scale. Finally, blood lactate was obtained to assess pre-exercise lactate values. For all participants, the TTE test then commenced at a constant intensity of 40% PPO with the constant intensity automatically increasing to 65% PPO after exactly 5 min. For the TTE test participants were instructed to pedal until volitional exhaustion that was defined as the point at which they voluntary chose to stop the test because they could no longer continue or when cadence dropped below 60 rpm for more than five consecutive seconds. During the TTE test, RPE and HR were recorded every minute, and at exhaustion.

The total recovery time that elapsed between the end of the 45-min cycling task to the start of the cycling TTE was *M* = 86 (*SD* = 5) min and was kept constant across the three visits for each participant. In the recovery time prior to and following the 40-min treatments participants were allowed to drink at libitum. On completion of the last visit, participants were thanked, and given a payment of £20. Cash prizes of £300, £100 and £50 were also offered for the first, second and third best performances respectively in the 10-min TT across the two experimental conditions. Best performances were calculated as the sum of the distance covered in the two 10-min TT's completed during EX+COG and EX+DOC. Cash prizes of £50 were also given for the longest TTE achieved during the cycling TTE test of each experimental visit.

Before every visit, participants were requested to eat the same light meal approximately 2 hr before arriving at the laboratory. They were also asked to sleep at least 7 hr the night before each visit, to consume approximately 35 ml/kg of body weight of water, to refrain from strenuous exercise, alcohol, and nicotine in the 24 hr prior to each session, and to avoid caffeine consumption in the 3 hr prior to each session. A checklist was completed at the start of each visit to verify compliance with these instructions. Each participant performed the three experimental visits at a similar time of the day (maximum 60 min difference) with a minimum of four days and a maximum of four weeks separating each session. All sessions were carried out in the same laboratory under a standardised environmental temperature of 19 ºC, and all physical tests were completed on the same electromagnetically braked cycle ergometer.

**Figure 1**

*Experimental Procedures*



*Note*. COG involved the same procedures as visit EX+COG, starting from blood lactate 1. HRV= heart rate variability; EEG=electroencephalogram; TTE= time-to-exhaustion test; Blood Lact= Blood lactate level, CT= cognitive task; doc= documentary control task.

## Materials

### *Experimental Treatments*

***Cognitive Task.*** The 40-min cognitive task in EX+COG and COG was composed of four sequential 10-min blocks. The first block consisted of a 10-min modified Stroop Colour Word task (Stroop, 1992) followed by a 10-min 2-back letter task, then another 10-min modified Stroop Colour Word task and lastly another 10-min 2-back letter task. This was to reduce adaptation to the 40-min cognitive task. During the 10-min Stroop tasks, one of four colour words (YELLOW, GREEN, BLUE, RED) appeared on screen, participants were asked to respond with the coloured key-button corresponding to the ink colour of the word presented independently of its meaning (i.e., if the BLUE word appeared in GREEN ink, they had to press the GREEN button). However, if the ink colour of the word was RED, they had to respond to the meaning of the word (i.e., if the BLUE word appeared in RED ink, they had to press the BLUE button). A total of 295 trials were presented for each 10-min block, with 40% of trials being incongruent (colour word and colour ink did not match), 36% congruent (colour word and colour ink matched) and 24% incongruent in meaning (colour word presented in red ink). During the 10-min 2-back tasks, white letters appeared sequentially in the centre of the black screen. Participants were instructed to respond to the target letters with the T key on the keyboard, and the not target letters with the P key. Target trials occurred when the presented letter matched the one that had appeared two trials before it in the presentation sequence. All other letters were considered as nontargets. Each 10-min 2-back task comprised of 297 trials; of this, 30% of trials were target trials and 70% were nontarget trials. In both the modified Stroop Colour Word task and the 2-back letter task, stimuli for each trial were presented at the centre of the black screen in uppercase for 500 ms with a 1500 ms inter-stimulus interval. At the beginning of the 40-min cognitive task, participants were instructed to respond as quickly and accurately as possible to every trial. Participants were also asked to refrain from head movements, maintain the same seated position, and look at the centre of the screen where the stimulus appeared for the duration of each 10-min block. This was to prevent artefacts in the accompanying EEG and HRV recordings. Participants were familiarised with the modified Stroop Colour Word task and the 2-back letter task for 5 min during the preliminary visit. Furthermore, they performed 24 practice trials for each task prior to the 40-min cognitive task. Performance feedback was only provided during familiarization and practice trials so that participants understood the requirements of each procedure. E-prime software (Psychology Software Tools, Pittsburgh, PA, USA) was used to develop and analysed offline the modified Stroop Colour Word task and the 2-back letter task. Response time and accuracy were then averaged for each of the four 10-min blocks.

***Documentary.*** During EX+DOC, the 40-min cognitive task was replaced with a 40-min documentary, “World Class Trains - The Venice Simplon Orient Express” (Pegasus-Eagle Rock Entertainment, 2004). This documentary has been previously used in mental fatigue research as a control condition (Marcora et al., 2009). It has been reported to be emotionally neutral and able to maintain stable cardiovascular activity (Silvestrini & Gendolla, 2007). Like the 40-min cognitive task, participants were instructed to refrain from head movements, to maintain the same seated position. The 40-min documentary was played without sound to mimic the silent condition of the 40-min cognitive task, and to prevent sound artefacts during EEG recording.

### *Psychological and Perceptual Measures*

**Brunel Mood Scale (BRUMS).** The subscales of fatigue, vigour and anger from the BRUMS (Terry et al., 2003) were rated on a 5-point scale (from 0 = *not at all* to 4 = *extremely*); each subscale consisted of four items, and participants rated each item based on how they currently felt.

**Positive and Negative Affect Schedule (PANAS).** The short version of the PANAS (Mackinnon et al., 1999) was used to measure affective state throughout each visit. The scale is composed of ten items: five related to positive affect and five to negative affect. These are rated on a 6-point scale ranging from *strongly disagree* to *strongly agree*. The positive and negative affect scales are scored separately by adding their respective values.

**Motivation.** Motivation to complete the 45-min cycling task was measured using a single item ("How motivated are you to perform the time trial on the cycle-ergometer?") rated on a 5-point Likert Scale (0 = *not at all*, 1 = *a little*, 2 = *somewhat*, 3 = *very much*, 4 = *extremely motivated*) immediately before starting the task. The same scale was used to rate the motivation toward the TTE test throughout the sessions ("How motivated are you to perform the next cycling task to exhaustion?").

**Resource-Demand Evaluations.** Participants were asked to rate their perceived coping resources for the TTE test and the perceived demand of the TTE test with a 2-item questionnaire "How able are you to cope with the demands of the upcoming cycling time-to-exhaustion test?" and "How demanding do you expect the upcoming cycling time-to-exhaustion test to be?" respectively (Moore et al., 2013). Both items were rated on a 6-point Likert scale, *not at all demanding / not at all able*; *extremely demanding / extremely able*. The responses were combined by subtracting the demand from the coping resource score to yield a single value ranging from -5 to +5. Positive values occur when perceived coping resources outweigh perceived demands, denoting a so-called challenge state which is typically characterized by physiological activity conducive to exercise, as might occur when one is well-recovered from previous tasks. Negative values occur when perceived demands outweigh perceived coping resources, denoting a so-called threat state typically characterized by physiological reactivity that is unconducive to exercise, and may reflect poor recovery and preparedness for the final exercise test (Seery, 2013).

**Perceived Recovery State.** The PRS scale, developed by Laurent et al. (2011), was used to measure subjective perception of individuals recovery state. To assess PRS individuals rated their recovery state on a 10-point scale ranging from a 0 (*very poorly recovered*) to 10 (*very well recovered*).

**NASA Task Load Index (NASA-TLX).** The NASA-TLX was used to evaluate subjective experience of workload. It includes six subscales, mental demand ("How much mental and perceptual activity was required?"), physical demand ("How much physical activity was required?"), temporal demand ("How much time pressure did you feel due to the rate or pace at which the task occurred?"), performance ("How successful do you think you were in accomplishing the goals of the task?"), effort ("How hard did you have to work to accomplish your level of performance") and frustration ("How irritating or annoying did you perceive the task?"). Each of the items is presented on a scale divided into 20 equal intervals anchored by bipolar descriptor (e.g., *Very Low/ Very High* and *Perfect/ Failure*). Participants rated each item at the end of the first physical task in EX+COG and EX+DOC, and at the end of the 40-min cognitive task / documentary in visits EX+COG, EX+DOC and COG. This score was multiplied by five, and the final score of each item ranged from 0 to 100. In the present study, the ratings recorded after the treatments are presented as a manipulation check of subjective workload of the cognitive task compared to documentary.

**Rating Scale of Mental Effort (RSME).** Subjective fatigue was assessed using the RSME (Zijlstra, 1993) which consist of a single item scored on a scale ranging from 0 to 150 with anchors including *absolutely no effort* (3) and *extreme effort* (114). Participants rated their level of mental effort at the end of the 40-min cognitive task / documentary in visits EX+COG, EX+DOC and COG. This scale was used as a manipulation check to assess the effect of the 40-min cognitive task on mental fatigue (e.g., van Der Linden et al., 2003).

**Rating of Perceived Effort (RPE).** RPE was recorded with the CR-10 (Borg, 1998). Anchors of *no effort* (0) to *maximal effort* (10) were established using standard instructions that were given to participants prior to the incremental test using the procedures described by Noble and Robertson (1996). During the TTE tests, participants were asked to rate on the scale based on how hard, heavy, and strenuous the physical task was in each moment (Marcora, 2010).

### *Physiological Measures*

**Blood Lactate.** For all blood lactate samples, a 0.3 μL sample of whole fresh blood was obtained from a fingertip on the non-dominant hand and was analysed immediately using a calibrated portable device (Lactate Pro LT-1710; Arkray, Shiga, Japan).

**Heart Rate Variability (HRV).** Beat to beat heart rate data were recorded continuously throughout each task via remote transmitter obtained from a wetted chest-strap and recorded on an accompanying wristwatch (RS800CX, Polar, Kempele, Finland). Beat to beat data were then used for HRV analysis during the three 5-min Flanker tasks and continuously during the 40-min cognitive task / documentary. The data were exported to the Polar Pro Trainer software (version 5), before further exportation to specific software for analysis (Kubios HRV Analysis version 3.0, The Biomedical Signals Analysis Group, University of Kuopio, Finland).

**Electroencephalogram (EEG).** EEG was captured from four active electrodes on the scalp positioned with a stretchable lycra cap following the 10-20 system (Jasper, 1958). The active electrodes were placed at Fz, F4, F3 and Oz and connected to a DC amplifier (Brainiquiry PET-4.0, neuroCare), with reference and ground electrodes respectively attached to the linked mastoids and FPz. Prior to electrodes' attachment, the sites on the scalp were abraded with a blunt needle and a combination of cream (Nuprep, Weaver) and alcohol wipes were used for mastoids sites to reduce skin impedance. Conductive gel (SignaGel, Parker) was applied to all recording sites and electrode impedance at each site was kept below 5kΩ. Cortical activity was recorded during the three 5-min Flanker task and throughout the 40-min cognitive task / documentary of each visit. The signals were digitised at 24-bit resolution and transmitted via Bluetooth at a sampling rate of 200 Hz to a computer running Bioexplorer (Cyberevolution) software.

**Flanker Task.** Participants performed a standard Flanker task to act as a "vanilla" condition to standardise EEG and HR recording throughout and across experimental visits (see Quintana & Heather, 2014). For the task, five arrows were presented in the centre of the black screen and participants were instructed to respond with the keyboard button corresponding to the direction that the central arrow was facing. The task consisted of neutral trials where the stimulus was accompanied by neutral symbols (i.e., - - < - - or - - > - -) and congruent trials in which the stimulus was presented with other arrows pointing in the same direction as the central arrow (i.e., > > > > > or < < < < <). The Q button was used for left responses and the P button was used for right responses. Stimuli were presented for 1500 ms with an 11000 ms inter-stimulus interval during which a fixation asterisk replaced the arrows. A presentation rate of 12500 ms for each trial meant that 24 trials were randomly presented for each 5-min recording. Right and left target arrows, as well as neutral and congruent trials, occurred with equal probability in each 5-min recording. Response time was averaged over the 5-min period and used as a manipulation check to assess the effect of the cognitive task on behavioural measures. Data were analysed off-line with the software E-Prime (Psychology Software Tools, Pittsburgh, PA, USA).

### ***Data Reduction***

**EEG.** Matlab (R2019a) was used to extract EEG data from the raw signals for offline analysis. The signal from Fz, F3, F4 and Oz was resampled offline at 256 Hz, and a 1 Hz high pass filter (cut off frequency 0.8 Hz and transition bandwidth 0.4 Hz) and 30 Hz low pass filter (cut off frequency 35 Hz and transition bandwidth 10 Hz) were applied. Continuous EEG data were manually corrected for eyes blinks artefacts. Time-series data were divided into 5 s epochs with 50% overlap and epochs containing voltage shifts greater than ± 100 μV were rejected. The resulting epochs were tapered with a Hanning window, and the power spectrum was derived from each retained epoch by a fast Fourier transformation with a spectral resolution of 0.2 Hz. For each recording, power within theta (4-7 Hz), alpha (8-13 Hz) and beta (14-20 Hz) frequency bands were averaged across epochs. Measures of theta-band power were used as a marker of mental fatigue (see Van Cutsem et al., 2017; Wascher et al., 2014).

**HRV**. Beat-to-beat variation in heart rate was analysed with the Kubios software (Kubios HRV Analysis 3.3.1, University of Eastern Finland, Kuopio). Prior to the analysis, artefacts were corrected with beat removal and linear interpolation (beats corrected per recording *M* = 3.25%, *SD* = 4.00%). Any recordings that required more than 10% of the beats to be corrected were considered to contain excess noise and were thereby discarded. This only occurred on two occasions. The analysis focused on the log-transformed root mean square of differences between adjacent normal RR intervals (log-RMSSD) (Task force, 1996). Log-RMSSD data were averaged over the 5-min Flanker task and over 5 min of each 10-min block of the 40-min cognitive task. The RMSSD was selected because it is a marker of cardiac vagal tone, hence an index that primarily reflects parasympathetic activity (Laborde et al., 2017; Task Force, 1996).

### Statistical Analysis

A priori-power analysis (G*Power) revealed that a sample of 18 participants would be powered enough to detect a medium effect ($f$=0.25) with $\beta$=80% in a repeated measures design with three experimental groups and three measurements. Based on previous research (e.g., Marcora et al., 2009; Pageaux et al., 2014; Van Cutsem et al., 2017), the mentally fatiguing manipulation was expected to have a medium effect size on the behavioural outcomes.

Before all the analyses, Shapiro-Wilk tested the assumption of normality. When normality was violated, data were checked with normality plot and non-parametric test, or transformations were used as reported. Greenhouse-Geiser correction was used where sphericity was violated. Significant main and interaction effects were investigated with pairwise comparisons with Bonferroni correction and contrast tests. For all the analyses, statistical significance was set at $p<.05$ (two-tailed). For the $F$-tests, the effect sizes were estimated with $\eta_p^2$ and values of .10, .25, and .40 reflect small, medium, and large effects (Cohen, 1988). For $t$-tests Cohen's $d$ with Hedges's correction ($g_{av}$)were calculated (see Formula 10 Lakens, 2014) with thresholds for small, moderate or large effects set at 0.2, 0.5, and 0.8 respectively (Cohen, 1988). All the analyses were conducted using the statistical package for social sciences (SPSS v. 24, IBM, Chicago, IL).

### *Manipulations Check*

Paired sample *t*-tests were used to compare the 45-min cycling tasks in condition EX+COG and condition EX+DOC. They specifically evaluated: motivation, TT performance (distance covered), TT mean cadence, maximal HR and RPE and blood lactate level at the end of the task. To examine mental fatigue induced by the 40-min cognitive task, Friedman tests compared the NASA-TLX scales and RSME on completion of 40-min cognitive tasks / documentary. Three (Condition; EX+COG, EX+DOC, COG) × 2 (Time; baseline, post-treatment) repeated measures ANOVAs analysed Flanker task response time (RT) and EEG.

### *Effect of Mental Fatigue on Recovery*

Due to the number and variety of recovery markers measured, and in-keeping with the aim of examining the psychological, physiological, and behavioural bases of recovery, the results are analysed and presented in three parts, with a short discussion after each, and then a general discussion integrates all our findings at the end. Furthermore, because the number of recordings gathered in COG condition differed from those of EX+COG and EX+DOC, we report both 2 Condition × 3 (or 4 depending on the measure) Time ANOVAs to examine the full range of timepoints that featured in the two EX conditions, and 3 Condition × 2 (or 3 depending on the measure) Time ANOVAs to examine all the timepoints that were common to all three experimental conditions (i.e., EX+COG, EX+DOC and COG).

***Part A*** examines the effect of mental fatigue on subjective measures. Two (Condition; EX+COG and EX+DOC) × 4 (Time; baseline, post 45-min cycling task, post treatment, before TTE) repeated measures ANOVAs were initially conducted to examine vigour, fatigue and PANAS at the four timepoints that featured in the EX+COG and the EX+DOC conditions. Vigour, fatigue, PANAS, TTE motivation and resource-demand balance scores were then subjected to separate 3 (Condition; EX+COG, EX+DOC and COG) × 3 (Time; post 45-min cycling task / baseline in COG, post treatment and before TTE) repeated measures ANOVAs and perceived recovery state to 3 × 2 repeated measures ANOVA, to analyse the three timepoints that were common to all conditions.

***Part B*** examines the effect of mental fatigue on behavioural outcomes, i.e., Flanker task response time and TTE performance. Flanker task response time was subjected to a 2 (Condition) × 3 (Time; baseline, post 45-min cycling task, post treatment) repeated measures ANOVA and then a separate 3 (Condition; EX+COG, EX+DOC and COG) × 2 (Time; post 45-min cycling task / baseline in COG, post treatment) repeated measures ANOVA to reflect the different number of times the Flanker task was performed across the different experimental conditions. One-way ANOVAs were used to compare the TTE performance.

***Part C*** examines the physiological variables recorded throughout the recovery period. Hence it includes 2 (Condition) × 3 (Time; baseline, post 45-min cycling task, post treatment) repeated measures ANOVAs and 3 (Condition; EX+COG, EX+DOC and COG) × 2 (Time; post 45-min cycling task / baseline in COG, post treatment) repeated measures ANOVAs on HRV and EEG Flanker task data. In addition, a 3 (Condition) × 2 (Time; post 45-min cycling task / baseline in COG and before TTE test) repeated measures ANOVA was performed on blood lactate.

# Results

## Manipulation Check

### *Continuous 45-min Cycling Task*

Table 1 reports descriptive statistics and *t*-test results of the 45-min cycling task data. Individuals were equally motivated to complete the 45-min cycling task. Moreover, HR and RPE at the end of the tests were similar and close to maximal values. Coupled with the similar distance covered, mean power output and cadence during the 10-min TT, the data indicate that individuals completed the 45-min cycling task in an equal state of high fatigue thereby establishing a need for recovery.

**Table 1**

*Descriptive and Statistics of the Time Trials Variables in EX+COG and EX+DOC*

| TT Variables | EX + COG | | EX + DOC | | $t$ (17)[a] | $p$ | $g_{av}$ |
|---|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | | | |
| Motivation | 3.39 | 0.85 | 3.39 | 0.78 | .00[b] | 1.00 | .00 |
| Distance (km) | 10.40 | 2.03 | 10.46 | 1.97 | .51 | .61 | .03 |
| Power (W) | 259 | 52 | 261 | 49 | .71 | .49 | .04 |
| HR mean (bpm) | 169 | 15 | 170 | 14 | .95 | .35 | .08 |
| Cadence (rpm) | 89 | 8 | 90 | 8 | .96 | .35 | .07 |
| HR end (bpm) | 179 | 15 | 179 | 14 | .70 | .50 | .05 |
| RPE end | 10.1 | 0.5 | 10.0 | 0.6 | .42 | .68 | .10 |
| Blood Lact (mmol/L) | 11.17 | 3.96 | 10.19 | 4.05 | 1.66 | .11 | .24 |

*Note*. TT=Time Trial; HR=Heart Rate; RPE=rating of perceived effort; Blood Lact= blood lactate; $g_{av}$ = Hedges'g for related samples

[a] degree of freedom for all the analyses

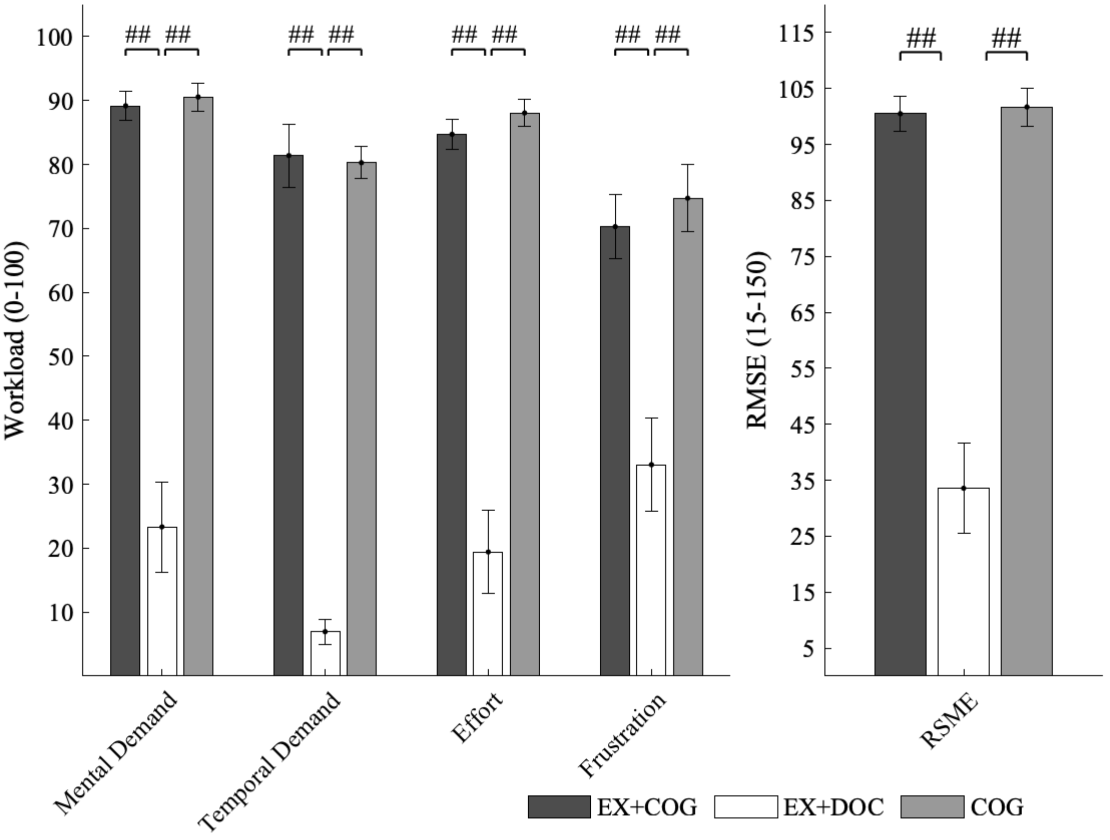
[b] *Z* and *p* from Wilcoxon signed ranks test

### *Mental Fatigue*

Means of the NASA-TLX and RSME scales are displayed in Figure 2. Mental demand, temporal demand, effort and frustration on the NASA-TLX and RSME were all significantly different between conditions. All scales were significantly greater immediately after the 40-min cognitive task in EX+COG and COG than they were after the documentary (EX+DOC), *p*-values≤.001. The scales did not differ between EX+COG and COG at the end of their respective 40-min cognitive tasks (*p*-values>.200). Together these results demonstrate that our 40-min cognitive task elicited a high and greater level of mental demand and effort than the 40-min documentary and indicate a successful manipulation of mental fatigue during the recovery period.

**Figure 2**

*NASA-TLX and Rating Scale of Mental Effort after the Cognitive Tasks or Documentary*



*Note*. *M*±*SE*. RMSE=Rating Scale of Mental Effort; Workload= NASA-TLX.

$^{\#\#}$ significantly different to EX+DOC (p<.001)

## Part A - Subjective Measures

### Part A – Results

#### *Fatigue and Vigour (BRUMS) and PANAS*

Two Condition × 4 Time ANOVAs revealed significant main effects of time for vigour ($F(2,30)=18.69$, $p<.001$, $\eta_\rho^2=.524$), fatigue, ($F(2, 32)=22.04$, $p<.001$, $\eta_\rho^2=.565$) and positive affect, ($F(2,35)=24.38$, $p<.001$, $\eta_\rho^2=.589$). The means are summarized in Table 2. In brief, vigour decreased, and fatigue increased from baseline to post 45-min cycling task then remained below (vigour) and above (fatigue) baseline-levels at the subsequent timepoints. Positive affect displayed an acute drop immediately after the treatments compared to the preceding timepoints but then recovered to baseline levels by the final pre TTE timepoint. There were no significant effects of condition for vigour, ($F(1,17)=0.73$, $p=.405$, $\eta_\rho^2=.041$), fatigue ($F(1,17)=0.094$, $p=.762$ $\eta_\rho^2=.006$) or for positive affect, ($F(1,17)=1.52$, $p=.235$, $\eta_\rho^2=.082$). Finally, there were no significant Condition × Time interactions (vigour: $F(3,51)=2.48$, $p=.072$, $\eta_\rho^2=.127$; fatigue: $F(3,51)=0.229$, $p=.876$, $\eta_\rho^2=.013$; positive affect: $F(3,51)=.432$, $p=.731$, $\eta_\rho^2=.025$). Wilcoxon Signed Ranked test did not reveal significant differences between conditions and across time in the negative affect schedule ($p$-values >.500).

When the condition without a prior 45-min cycling task (COG) was added to the analysis, results still reported a significant main effect of time. Vigour and positive affect decreased, and fatigue increased from post-cycling task / baseline in COG to post 40-min treatment in all conditions. Vigour ($F(2,34)=8.50$, $p=.001$, $\eta_\rho^2=.333$) and positive affect ($F(2,34)=5.10$, $p<.012$, $\eta_\rho^2=.231$) presented a significant main effects of condition. Vigour was higher in COG than in EX+DOC and EX+COG, while positive affect was higher in COG compared to EX+DOC only. Fatigue in addition to the main effect of condition ($F(2,26)=6.46$, $p<.009$, $\eta_\rho^2=.275$) demonstrated a significant Condition × Time interaction ($F(3,46)=7.46$,

$p<.001$, $\eta_p^2=.305$) as it was lower in COG compared to EX+COG and EX+DOC after the cycling task (corresponding to baseline in COG, *p*-values<.001) and before the TTE tests (*p*-values <.040). However, fatigue did not differ between conditions after the 40-min treatments (*p*=1.000 for all comparisons). The negative affect schedule was not significantly different between conditions at any time (*p*-values >.400).

**Table 2**

*Fatigue, Vigour and Positive Affect in EX+COG, EX+DOC and COG*

| Measures | | EX+COG | EX+DOC | COG | |
|---|---|---|---|---|---|
| | Time | *M* (*SD*) | *M*(*SD*) | *M*(*SD*) | Direction of change |
| Fatigue | 1 | 2.2 (2.1) | 2.2 (1.6) | | |
| | 2 | 7.7 (4.0) | 7.9 (3.3) | 2.2 (1.7) * | ↑ |
| | 3 | 7.5 (4.3) | 7.0 (2.5) | 6.9 (3.4) | |
| | 4 | 5.9 (3.1) | 5.6 (2.9) | 3.6 (2.7) * | |
| Vigour | 1 | 10.6 (2.9) | 10.3 (2.9) | | |
| | 2 | 8.8 (4.5) | 7.3 (3.7) | 10.8 (2.7) * | |
| | 3 | 4.9 (3.2) | 5.3 (2.3) | 6.1 (3.7) * | ↓ |
| | 4 | 7.3 (3.6) | 7.2 (2.0) | 9.4 (3.6) * | |
| Positive Affect | 1 | 24.10 (4.8) | 22.7 (4.7) | | |
| | 2 | 21.8 (6.4) | 21.3 (5.5) | 23.7 (4.3) * | |
| | 3 | 16.8 (5.8) | 15.6 (4.9) | 17.8 (6.3) * | ↓ |
| | 4 | 19.1 (6.1) | 18.7 (4.8) | 21.6 (5.9) * | ↑ |

*Note.* 1= baseline for EX+COG and EX+DOC; 2= before treatments (COG or DOC); 3= after treatments; 4= prior to the TTE test. Arrows indicate significant changes over time across conditions

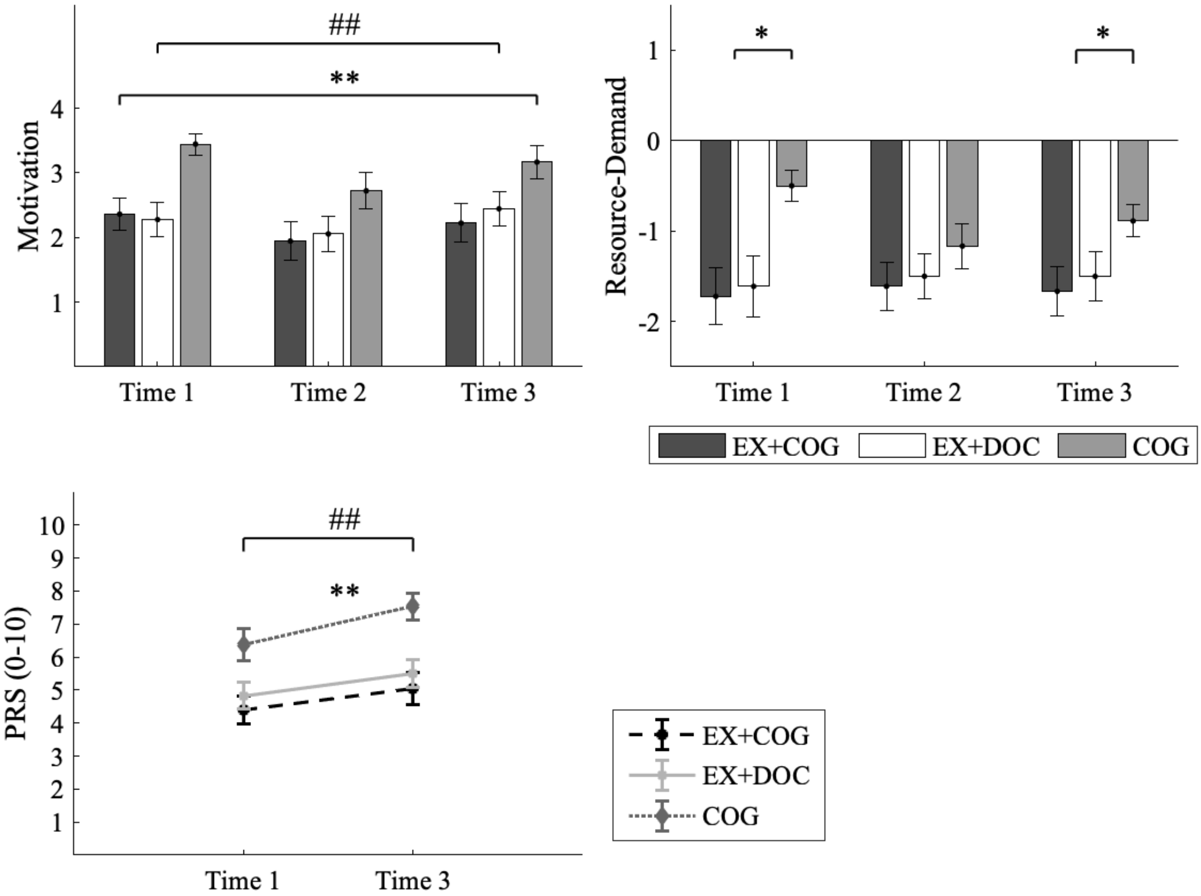
*COG significantly different from EX+COG and EX+DOC

### *Perceived Recovery State, Motivation and Resource-Demand Evaluations*

Statistical outcomes are summarized in Table 3 and means are reported in Figure 3. In brief, condition main effect for PRS confirmed that the 45-min cycling task in EX+ COG and EX+DOC significantly hampered perceived recovery state compared to COG and time main effect showed that PRS increased slightly before the TTE tests. Likewise, the 45-min cycling task in EX+ COG and EX+DOC significantly reduced motivation for the TTE tests and elicited a threat appraisal for all subsequent timepoints when compared to the cognitive task only condition (COG). In COG, the 40-min cognitive task also reduced motivation for the TTE tests, while the resource-demand evaluation score experienced a temporarily drop after the 40-min.

**Figure 3**

*Motivation, Resource Demand Evaluations and Perceived Recovery Scale Period*



*Note.* Motivation (upper-left) and resource-demand (upper-right), negative values indicate less coping resources (threat state). Perceived recovery scale (lower panel). *M*±*SE*. Time 1: after the 45-min cycling task / baseline in COG; time 2: after the treatments (COG or DOC); time 3: prior to the TTE.

# Significant main effect of time (*p*<.05); * Significant difference in COG (**p*<.05, ***p*<.001)

**Table 3**

*Two-way ANOVA Results for Perceived Recovery Scale, Motivation and Resource-Demand Evaluations*

| Dependent Variables | Effect | *df* | *F* | *p* | $\eta_p^2$ | Direction of change |
|---|---|---|---|---|---|---|
| Perceived Recovery State | Condition | 2, 32 | 13.00 | .00 | .45 | * |
| | Time | 1, 16 | 16.42 | .00 | .51 | ↑ |
| | Condition × Time | 2, 32 | .44 | .65 | .03 | |
| Motivation | Condition | 2, 34 | 14.65 | .00 | .46 | * |
| | Time | 2, 34 | 7.54 | .00 | .31 | ↓ |
| | Condition × Time | 3, 48 | .97 | .41 | .05 | |
| Resource-Demand Evaluation | Condition (Time1) | 2 | 14.56[b] | .00 | | * |
| | Condition (Time 2) | 2 | 2.00[a] | .37 | | [a] |
| | Condition (Time 3) | 2 | 8.54[a] | .01 | | * |

*Note*. Arrows indicate significant changes over time across conditions

* COG significantly different from EX+COG and EX+DOC

[a] significant difference over time in COG.

[b] $\chi^2$ from non-parametric Friedman test.

## Part A – Discussion

After the 45-min cycling task in EX+COG and EX+DOC, the fatigue dimension of mood raised from ~ 2 to ~ 7.5 and then, remained above baseline throughout the entire recovery period. Moreover, subjective fatigue increased after the cognitive task alone in COG (from ~ 2 to ~ 6.9). Yet, fatigue level after the cognitive task in EX+COG was not different from fatigue registered after the documentary (EX+DOC) and was not different from the fatigue recorded right after the 45-min cycling task during the same visit (EX+COG). The COG condition findings confirm that cognitive tasks can be fatiguing, but the pattern of results from the other conditions indicate that fatigue reported after the treatments in EX+COG and EX+DOC was mostly driven by fatigue from the initial bout of exercise.

Vigour and positive affective state decreased significantly after the treatments (cognitive task and documentary) across the three conditions, and, interestingly, were not affected after the 45-min cycling task in EX+COG and EX+DOC. Previous research has characterised mental fatigue via increased tiredness and decreased self-reported energy (e.g., Hopstaken et al., 2015a; Hopstaken et al., 2015b; Lorist et al., 2009). However, after the 40-min treatments (COG and DOC), vigour and positive affect were higher in COG compared to the other conditions with the 45-min cycling task, indicating that the intense exercise had a delayed and detrimental effect on affect and mood state. Previous research showed that exercise-induced fatigue is associated with reduced vigour when it accumulates over training sessions (Halson et al., 2002) as well as when acute post-exercise recovery follows strenuous exercise (Hassmen & Blomstrand, 1991, Broatch et al., 2014). Vigour and affective state results also agree with the lower resource-demand evaluations score and the lower motivation reported in EX+COG and EX+DOC compared to COG suggesting that low vigour driven by previous physical tasks adversely affected motivation and the perceived resource-demand for the upcoming cycling TTE. Gergelyfi et al. (2015) reported that fatigue induced by prolonged cognitive tasks lowers motivation to continue with any further cognitive activity and reduces perceived competence. In the COG condition, the temporary decrease in the resource demand evaluation score (indicative of a threat appraisal) after the cognitive task, provides new evidence that the adverse impact of fatigue on resource and demand balance transfers across different types of fatiguing task.

## Part B - Behavioural Measures

### Part B – Results

#### *Flanker Task Response Time*

Response time means are reported in Table 4. The 2 Condition × 3 Time ANOVA on response time revealed a significant main effect of time ($F(2,27)=10.71$, $p=.001$, $\eta_\rho^2=.387$) and

Condition × Time interaction (*F*(1,22)=4.86, *p*=.031, $\eta_\rho^2$=.222). After the 45-min cycling task response time in EX+COG was faster than the response time in EX+DOC (*t*(17)=2.58, *p*=.019, $g_{av}$=.216), while after the 40-min treatments it was slower in EX+COG compared to EX+DOC (*t*(17)=2.27, *p*=.036, $g_{av}$=.461). Furthermore, response time in EX+COG increased significantly after the 40-min cognitive task compared to the response time at baseline and the response time after the cycling task. Response time remained stable over time in EX+DOC. The second ANOVA 3 Condition × 2 Time revealed again a main effect of time (*F*(1,17)=17.98, *p*=.001, $\eta_\rho^2$=.514) and a significant Condition × Time interaction (*F*(2,26)=7.54, *p*=.005, $\eta_\rho^2$=.307). Response time increased significantly after the 40-min treatments with response time in EX+COG and COG reporting the largest increase, while response time in EX+DOC had a smaller increment (EX+COG: *t*(17)=3.80, *p*=.001, $g_{av}$=.801; COG: *t*(17)=3.86, *p*=.001, $g_{av}$=.555; EX+DOC: *t*(17)=2.22, *p*=.040, $g_{av}$=.215).

### ***Time-to-Exhaustion Test***

TTE tests were respectively *M*(*SD*), 1519 (907) s in EX+COG, 1427 (662) s in EX+DOC and 2197 (848) s in COG. ANOVA confirmed a significant difference between conditions, *F*(2,34)=22.24, *p*<.001, $\eta_\rho^2$=.567. Pairwise comparisons revealed that TTE performance was significantly longer for COG than EX+COG (*p*<.001, $g_{av}$=.744) and EX+DOC (*p*<.001, $g_{av}$=.994). However, TTE performance did not differ between EX+COG and EX+DOC (*p*=1.000, $g_{av}$=.114). RPE attained at the end of the three TTE tests were *M*(*SD*), 10.11(0.53), 10.19(0.57), and 10.19(0.57) in EX+COG, EX+DOC and COG, respectively. HR at exhaustion were *M*(*SD*), 94(5)%, 95(4)%, and 95(3)% in EX+COG, EX+DOC and COG, respectively (% of maximal HR derived from the maximal incremental ramp test). RPE and HR at exhaustion did not differ between conditions indicating that individuals chose to disengage from the TTE test at a similar and very high level of effort in all three conditions.

## Part B – Discussion

In line with the pattern of mood and positive affect, the Flanker task response time increased significantly after the treatments (COG and DOC). However, the increment was greater after the 40-min cognitive tasks in EX+COG and COG (effect size: 0.80 and 0.55 respectively) than after the 40-min documentary (effect size: 0.20). This indicated that the cognitive task compared to the documentary had a selective and detrimental effect on cognition. This increased response time could reflect less efficient information processing and has been previously reported after 20 min of sustained cognitive activity (e.g., Mockel et al., 2015; Lorist et al., 2009).

On the other hand, TTE performance during the final exercise bout was not significantly different between EX+COG and EX+DOC conditions, though TTE was significantly lower in those conditions compared to the TTE in COG. The detrimental effect of mental fatigue on performance has been widely reported (see Van Cutsem, Marcora et al., 2017 for a review). However, Van Cutsem, De Pauw, et al. (2017) showed that when endurance performance was already reduced by a hot environment, mental fatigue did not result in further performance reductions. The authors hypothesized that a "floor effect" existed for performance. Accordingly, it is plausible that the detrimental effect of the 45-min cycling task on TTE performance in the present study prevented any further decline in performance due to the combined effect of physical-induced and cognitive-induced fatigue in EX+COG compared to EX+DOC.

## Part C - Physiological Measures

## Part C – Results

### *Flanker Task HRV*

The RMSSD means, indices of HRV, are reported in Table 4. The 2 Condition × 3 Time ANOVA on log-RMSSD revealed a significant main effect of time (*F*(1,21)=35.79,

$p<.001$, $\eta_{\rho}^{2}=.678$), but no difference between conditions ($F(1,17)=1.91$, $p=.185$, $\eta_{\rho}^{2}=.101$) and no Condition × Time interaction ($F(2,34)=0.95$, $p=.399$, $\eta_{\rho}^{2}=.053$). Log-RMSSD decreased from baseline to post 45-min cycling task, then increased in the subsequent timepoint, yet remaining below baseline-level. The second 3 Condition x 2 Time ANOVA on log-RMSSD ($N=16$ because HR data of two participants contained high percentage of artefacts) revealed significant main effects of condition ($F(1,20)=26.40$, $p<.001$, $\eta_{\rho}^{2}=.638$), time ($F(1,15)=37.03$, $p<.001$, $\eta_{\rho}^{2}=.712$) and a significant Condition × Time interaction ($F(2,30)=12.89$, $p<.001$, $\eta_{\rho}^{2}=.462$). Log-RMSSD in COG was significantly higher compared to the values recorded in EX+COG and EX+DOC. Log-RMSSD increased significantly after the treatments in EX+DOC and EX+COG; a nonsignificant increase was found after the 40-min cognitive task in COG ($p=.094$).

### *Flanker Task EEG*

EEG data are reported in Table 5. The 2 Condition × 3 Time ANOVAs on theta-band power revealed a main effect of time in all sites (Fz: $F(2,28)=8.31$, $p=.001$, $\eta_{\rho}^{2}=.372$; F3: $F(2,28)=8.01$, $p=.002$, $\eta_{\rho}^{2}=.364$; F4: $F(2,28)=12.06$ $p<.001$, $\eta_{\rho}^{2}=.463$; and Oz: $F(2,28)=9.62$, $p=.001$, $\eta_{\rho}^{2}= .407$). Theta-band power increased significantly after the 40-min treatments compared to the previous recordings in all sites. No differences between conditions were found at any time. ANOVAs on alpha-band power showed a main effect of time in the four sites. Alpha Oz also reported a significant Condition × Time interaction. Fz alpha-band power increased significantly after the cycling task and then levelled off after the 40-min treatments. In contrast, F3 and F4 alpha-band power increased significantly after the 40-min treatments. Alpha-band power in Oz increased after the cycling task only in EX+COG and increased from post-cycling task recording to the post-documentary recording in condition EX+DOC. Hence, it was not significantly higher after the cycling task in EX+COG compared to EX+DOC ($p=.068$). The second 3 Condition x 2 Time ANOVAs on theta-band power revealed again a significant main effect of time for all sites. Specifically, it increased significantly after the 40-min treatments (p-values<.010) similarly across conditions. ANOVAs on alpha-band reported a significant main effect of time as alpha-band power was higher after the 40-min treatments compared to the previous recording in all sites and this increment was similar across conditions.

**Table 4**

*Flanker Task Response Time and Heart Rate Variability in EX+COG EX+DOC and COG*

| Measures | | EX+COG | EX+DOC | COG | |
|---|---|---|---|---|---|
| | Time | *M* (*SD*) | *M*(*SD*) | *M*(*SD*) | Direction of change |
| Reaction time (ms) | 1 | 492 (84) | 497 (79) | | |
| | 2 | 475 (64) | 489 (66) | 480 (85) | |
| | 3 | 568 (187) | 506 (79) | 531 (92) | ↑ |
| RMSSD (ms) | 1 | 1047 (156) | 1062 (162) | | |
| | 2 | 739 (128) | 731 (134) | 1075 (138) * | ↓ |
| | 3 | 906 (141) | 889 (152) | 1105 (152) * | ↑ |

*Note*. RMSSD= root mean square of successive RR difference; 1= baseline for EX+COG and EX+DOC; 2= before treatments (COG or DOC); 3= after treatments; 4= prior to the TTE test. Arrows indicate significant changes over time across conditions

* COG significantly different from EX+COG and EX+DOC

**Table 5**

*EEG data for Mental Fatigue and Recovery in EX+COG EX+DOC and COG*

| Measures | | | EX+COG | EX+DOC | COG | Direction of change |
|---|---|---|---|---|---|---|
| Frequencies Band | | Time | *M* (*SD*) | *M*(*SD*) | *M*(*SD*) | |
| Theta ($\mu V^2$/Hz) | | 1 | 0.50 (0.17) | 0.50 (0.18) | | |
| | Fz | 2 | 0.48 (0.18) | 0.49 (0.18) | 0.50 (0.19) | |
| | | 3 | 0.56 (0.24) | 0.55 (0.21) | 0.57 (0.23) | ↑ |
| | | 1 | 0.39 (0.10) | 0.39 (0.14) | | |
| | F3 | 2 | 0.39 (0.14) | 0.39 (0.12) | 0.42 (0.14) | |
| | | 3 | 0.47 (0.19) | 0.45 (0.15) | 0.48 (0.18) | ↑ |
| | | 1 | 0.43 (0.14) | 0.42 (0.14) | | |
| | F4 | 2 | 0.43 (0.15) | 0.44 (0.15) | 0.44 (0.16) | |
| | | 3 | 0.53 (0.23) | 0.50 (0.19) | 0.52 (0.19) | ↑ |
| | | 1 | 0.21 (0.12) | 0.19 (0.10) | | |
| | Oz | 2 | 0.21 (0.12) | 0.18 (0.10) | 0.22 (0.13) | |
| | | 3 | 0.24 (0.15) | 0.22 (0.13) | 0.23 (0.12) | ↑ |
| Alpha ($\mu V^2$/Hz) | | 1 | 0.34 (0.23) | 0.34 (0.21) | | |
| | Fz | 2 | 0.33 (0.19) | 0.31 (0.15) | 0.30 (0.17) | |
| | | 3 | 0.35 (0.23) | 0.32 (0.17) | 0.32 (0.16) | ↑ |
| | | 1 | 0.29 (0.17) | 0.28 (0.16) | | |
| | F3 | 2 | 0.28 (0.14) | 0.27 (0.11) | 0.28 (0.14) | |
| | | 3 | 0.33 (0.20) | 0.29 (0.12) | 0.31 (0.13) | ↑ |
| | | 1 | 0.31 (0.18) | 0.31 (0.18) | | |
| | F4 | 2 | 0.31 (0.16) | 0.29 (0.13) | 0.28 (0.15) | |
| | | 3 | 0.35 (0.20) | 0.31 (0.15) | 0.32 (0.15) | ↑ |
| | | 1 | 0.59 (0.75) | 0.56 (0.71) | | |
| | Oz | 2 | 0.60 (0.86) | 0.49 (0.71) | 0.44 (0.52) | |
| | | 3 | 0.59 (0.78) | 0.60 (0.86) | 0.48 (0.56) | ↑ |

*Note*. 1= baseline for EX+COG and EX+DOC; 2= before treatments (COG or DOC); 3= after treatments; 4= prior to the TTE test. Arrows indicate significant changes over time across conditions

### *Blood Lactate*

ANOVA on blood lactate level (*N*=16) revealed main effects of condition (*F*(2, 30)=63.62, *p*<.001, $\eta_\rho^2$=.809) and time (*F*(1,15)=60.36, *p*<.001, $\eta_\rho^2$=.801) and a significant Condition × Time interaction (*F*(2,30)=39.20, *p*<.001, $\eta_\rho^2$=.723). Lactate level in EX+COG and EX+DOC increased during the recovery period and did not differ between the two conditions at any point. Lactate level in COG remained stable throughout the visit and was lower compared to the other conditions at all timepoints (*p*-values<.001).

## Part C – Discussion

In accordance with previous research (e.g., Stewart et al., 2014; Stanley et al., 2014), parasympathetic activity, indicated by RMSSD, was reduced after the 45-min cycling task. Although it increased during the recovery period in EX+COG and EX+DOC, it remained below its baseline level throughout the entire recovery period. Importantly, RMSSD did not differ significantly at any point between the EX+DOC and EX+COG conditions. This implies that participants did not fully recover from the 45-min cycling task during our 90-min recovery period, and that cognitive activity during the recovery period did not delay recovery compared to the documentary-watching control condition. Moreover, RMSSD during the cognitive task in COG showed a temporary reduction reflecting the modulation of parasympathetic activity during the cognitive task (Supplementary Material, HRV during the interventions). This indicates that the cognitive task did prompt some parasympathetic disturbance, but this was not detected in the EX+COG condition because vagal tone was so suppressed by the 45-min cycling and any additional effect of cognitive activity on vagal tone appeared to be masked.

The EEG power spectral analysis revealed that power in the theta and alpha bands increased after the treatments in all conditions. Increased theta-band power has been previously reported during sustained cognitive tasks (e.g., Wascher et al., 2014, 2; Boksem et al., 2005), hence, increased theta band power has been suggested as a marker of mental fatigue (Van

Cutsem, Marcora et al., 2017). Similarly, Boksem et al (2005) and Lorist et al. (2009) reported an increase in theta- and alpha-band power when EEG spectral power was recorded continuously for two hours of cognitive tasks. Lorist et al. (2009) provided participants with monetary incentives before the last block of the cognitive task and found that the motivation reversed the decline in cognitive performance induced with mental fatigue. Interestingly, the power spectrum increment was not affected by their motivation manipulation (i.e., power of alpha and theta band continued to increase despite the performance improvement). The authors argued that this widespread, unspecific and non-functional synchronization of neuronal activity may reflect a state of mental fatigue elicited with time on task. In accordance with that, Klimesh et al. (1999) reported that increased alpha and theta band power during the wake-sleep cycle reflect decreased alertness and increased sleepiness. Besides confirming these previous findings, our results suggest that this increment in EEG spectral power due to fatigue is sustained across different types of tasks. That is, the 45-min cycling task in EX+COG and EX+DOC and the 40-min cognitive task in COG induced a similar increase of EEG spectral power, which reflected a state of decreased vigour, increased subjective fatigue, low positive affect, and less efficient information processing.

## General Discussion

We sought to fill an important gap in the literature by identifying what happens to markers of acute recovery when a mentally challenging task takes place immediately after the completion of demanding physical exercise. RSME and NASA-TLX scales indicated that the cognitive task we used was highly demanding, and most importantly it elicited greater mental effort compared to the control task (documentary). However, contrary to what we had hypothesised, a mentally fatiguing task immediately following strenuous physical exercise had little impact on acute recovery from previous exercise. Post-exercise recovery was operationalized as the temporary changes over time of several physiological and psychological markers as summarized in our mini discussions above, and as further integrated in our *Mechanism* section below.

**Mechanism**

Altogether our results suggest that the 45-min cycling task in condition EX+COG and EX+DOC elicited a temporary sympathoexcitatory effect reflected by the suppression of the parasympathetic activity (i.e., RMSSD index of heart rate variability). Throughout the recovery period, the sympathoexcitatory effect receded and was replaced by a state of fatigue with reduced cortical activation (indicated by elevated levels of theta- and alpha-band power), reduced information processing, low self-reported vigour and high self-reported fatigue. A similar state was induced in COG when individuals underwent the cognitive task immediately before the TTE tests without prior 45-min exercise. However, all of the above variables indicated better recovery in this COG condition This suggests that even though acute recovery is not altered when a mental challenge is introduced immediately after demanding endurance exercise, prior demanding endurance exercise itself, both alone and with the addition of mental fatigue, is significantly more detrimental to these recovery markers than prior mental fatigue alone and may even mask effect of mental fatigue.

The exercise-induced and cognitive-induced subjective fatigue in the present study were characterized by a similar and low-level of neurophysiological arousal (increased alpha and theta band power) which may explain why the effect of the two stressors on TTE tests did not combine to have additive effects on performance. Accordingly, the 45-min cycling task also had a greater negative impact on positive affect, motivation and demand resource-evolutions than the subsequent treatment tasks.  However, it remains to be established whether this “floor effect” on performance depends upon the experimental conditions or it is present even when mental fatigue is elicited with sustained cognitive activities of everyday tasks (job or educational related cognitive activities).

An alternative interpretation for this result could be drawn from the cognitive performance of the 40-min cognitive tasks in EX+COG and COG (Supplementary Materials). Stroop task accuracy in the incongruent trials was greater after the 45-ming cycling in EX+COG compared to COG indicating that the endurance exercise facilitated Stroop performance. Based on that, it is plausible that the physical task could postpone the rise of mental fatigue thanks to a facilitative effect on cognitive functions. Hence, the lack of effect of mental fatigue on post-exercise recovery is partly due to the beneficial consequence of acute exercise on cognitive functions. Several meta-analyses found a small positive effect of acute exercise on cognitive functions (Chang, et al., 2012; Lambourne, & Tomporowski, 2010; Ludyga, et al., 2016), though results from the singular investigations were highly heterogeneous and several variables were showed to moderate the relationship, for instance the exercise intensity. Accordingly, the majority of the studies pointed to the Yerkes and Dodson law of the inverted-U relationship between arousal and performance according to which moderate intensity, but not high, or low intensity activation should enhance cognitive performance. Overall, our results support that in trained individuals strenuous exercise had an initial benefit on Stroop performance in accordance with previously reported findings (e.g., Hogervorst et al., 1996; Sibley et al., 2006). However, this benefit did not last through the entire treatment and reaction time deteriorated in the Flanker task performed about 65 min after the exercise. Hence, it seems that when strenuous exercise is followed by sustained cognitive activity attentional processing could be impaired by the cumulative effect of the exercise-induced and mental fatigue (see also Moore et al., 2012). Although the effect of exercise on cognitive functions was not a primary topic of this investigation, our results encourage future research to take into account fatigue-induced effects of strenuous exercise when studying these processes.

Notably, when looking at EEG power spectrum recorded throughout the treatments, frontal theta-band power was sensitive to the contextual changes of the cognitive task. Specifically, frontal theta band power was greater during the Stroop task compared to 2-back task (see Supplementary Materials). This indicates that the assessment over time and between different conditions is necessary to fully understand the cortical activity underpinning cognitive fatigue and disentangle its adjustments related to effort, habituation and fatigue. Likewise, a temporary reduction of HRV was present during the cognitive task, however this could not be found when looking at pre-post data only.

### Limitation and Future Directions

We implemented a multidisciplinary approach to investigate the effect of a mentally fatiguing task on post-exercise recovery. Through this method, we linked different measures (e.g., behavioural, psychological and physiological variables) and provide novel insights into post-exercise recovery as well as into mental fatigue. However, some limitations should be considered when interpreting the results. Firstly, our manipulation lasted 40 min based on the recommendation that a minimum of 30-min cognitive task could be necessary to elicit mental fatigue (Van Cutsem et al., 2017). However, because the effect of acute exercise could have partly counteracted mental fatigue, longer manipulations could provide stronger tests of the effects of mental fatigue on recovery. On the same line, the sympathoexcitatory effect of exercise could have partially masked the effect of the cognitive task on some variables (e.g., HRV, mood state), it is possible that placing the treatments 90 min (see Stanley et al., 2013) after the first cycling task would help clarify the independent and cumulative effect of the cognitive task on each variable assessed. Future studies on mental fatigue and recovery could also benefit from using a longitudinal approach to overcome the acute effect of exercise. This approach would also allow study of the relationship between mental fatigue and performance in a real scenario and would help determine the generalisability of mental fatigue findings outside laboratory-based tasks. Moreover, it should be highlighted that the modest sample size may have played a role in limiting the significance of some statistical comparisons. Due to the large set of measures adopted, the power of the present study was computed at the expenses of some outcomes. In particular, the study could be underpowered to detect the small effect that the manipulations had on some self-reported and physiological measures (e.g., Quintana et al., 2017) which could require greater sensitivity. Hence, this limitation should be considered when interpreting the results of these measures. Lastly, it should be noted that participants in the current study completed on average eight hours training p/week and were all in employment or were university students. On one hand, it is possible that they were already used to alternating exercise training sessions with cognitive work/study duties hence, the treatment could have had smaller effect on them than would be expected on others who are less practised at both cognitive and exercise work. On the other hand, we cannot exclude that some may have started the visits after a workday and, hence, were already mentally fatigued.

## Conclusion

The present study investigated the effect of mental fatigue on acute recovery from strenuous exercise. Our results showed that mental fatigue did not significantly influence acute short-term recovery and in particular strenuous exercise resulted in much greater disturbances of the psychophysiological markers assessed compared to the prolonged cognitive activity. Although, in general, the cognitive task after strenuous exercise did not affect the psychophysiological markers of recovery differently from the documentary, we found that it could have a selective, detrimental effect on response time. Furthermore, we found that a similar state of low physiological arousal underlies fatigue induced with either strenuous exercise or sustained cognitive activity.

## Supplementary Materials

Below are reported supplementary data and analyses of EEG, HRV and cognitive performance (response time and accuracy % of error) recorded during the 40-min treatments and supplementary analyses of TTE variables, i.e., mean cadence and RPE and HR measured during the TTE tests.

### Supplementary Analyses for the 40-min Treatments

To investigate the effects of conditions and time-on-task on the physiological variables, the EEG time-series data recorded during the treatments were divided into eight 5 min intervals and then the two 5 min blocks corresponding to the cognitive tasks of the treatments (i.e., 10-min Stroop, 10-min 2-back, 10-min Stroop, 10-min 2-back task) were averaged. The log-RMSSD was computed for the 10-min blocks of each treatment. Power of theta- and alpha-band in the frontal and occipital channels and log-RMSSD were subjected to 3 (Condition; (EX+COG, EX+DOC and COG) × 2 (Block; first and second block of each task) × 2 (Task; Stroop and 2-back) repeated measures ANOVA. To further examine the effect of condition and time-on-task on behavioural response, the cognitive tasks in COG and EX+COG were compared. Separate 2 (Condition; EX+COG and COG) × 2 (Block; 1st 10-min and 2nd 10-min blocks) ANOVAs on the response time and accuracy (log transformed % of error) of the Stroop task were run for each type of trials (congruent, incongruent and incongruent-red trials). Two × 2 repeated measures ANOVAs were run on response time (log transformed) and accuracy (log transformed % of error) of the 2-back task for each type of trial (target and nontarget trials). $N$=17 in cognitive performance analyses because the software failed to record the response time data of one individual.

#### *Cognitive Task Performance EX+COG and COG*

ANOVAs on Stroop task response time did not reveal significant main effects, however the Block × Condition interactions were significant for the incongruent ($F(1,16)=8.84$, $p=.009$,

$\eta_\rho^2=.356$) and incongruent-red trials ($F(1,16)=4.86$, $p=.043$, $\eta_\rho^2=.233$). The Stroop task accuracy reported main effects of block ($F(1,16)=7.99$, $p=.012$, $\eta_\rho^2=.333$), and condition ($F(1,16)=9.73$, $p=.007$, $\eta_\rho^2=.378$) on the incongruent trials. The main effect of block was also present for the incongruent-red trials ($F(1,16)=9.43$, $p=.007$, $\eta_\rho^2=.371$). No other main effects or interactions were found. Response time improved over blocks especially for COG incongruent trials and remained stable throughout in EX+COG. Accuracy of the incongruent and incongruent-red trials improved over blocks in both conditions indicating a possible learning/habituation that attenuate the Stroop task interference. Importantly, the strenuous exercise had a beneficial and selective effect on the incongruent trials accuracy that was higher in EX+COG than in COG.  Results are summarised in Figure S4 and S5.

ANOVAs on the 2-back task response time revealed a significant main effect of block as the response time improved significantly in the second block across conditions and trials (target: $F(1,15)=4.99$, $p=.041$, $\eta_\rho^2=.250$; nontarget: $F(1,15)=12.06$, $p=.003$, $\eta_\rho^2=.446$). The 2-back task accuracy did not report any main effect. Accuracy of the target trials tended to improve from block 1 to block 2 in COG while remaining stable in EX+COG, however the Condition × Block interaction was nonsignificant ($F(1,15)=4.19$, $p=.059$, $\eta_\rho^2=.218$).

### ***Heart Rate Variability during the Treatments***

Main effects of condition ($F(2,26)=22.13$, $p<.001$, $\eta_\rho^2=.630$), block ($F(1,13)=32.41$, $p<.001$, $\eta_\rho^2=.714$), and task ($F(1,13)=7.97$, $p=.014$, $\eta_\rho^2=.380$), and a significant Condition × Block interaction ($F(2,26)=5.62$, $p=.009$, $\eta_\rho^2=.302$) were found in log-RMSSD. Log-RMSSD was significantly lower in EX+COG and EX+DOC compared to COG for every block of the treatments ($p$-values $<.005$). It did not differ at any point between EX+COG and EX+DOC ($p$-values$>.300$). Within the EX+COG cognitive task, log-RMSSD was significantly lower in the first two blocks of each task (block 1 and 2) compared to the last two blocks of each task (block 3 and 4, $p$-values $\leq.002$). Likewise, in COG log-RMSSD was significantly reduced in the first two blocks compared to the last two blocks when it increased. In EX+DOC it was lower in block 1 than block 3 ($p=.002$) and 4 ($p=.009$) and block 2 compared to 3 ($p=.010$). Overall, the 45-min cycling induced a significant and persistent reduction in HRV that continued throughout the entire treatment. Moreover, the cognitive task, when performed alone (COG), induced a significant, yet temporarily, reduction in HRV. However, this suppression was not evident when the cognitive task had followed the 45-min cycling task.

### *EEG during the Treatments*

Spectral power was averaged across the three frontal sites so that two separate analyses were run for frontal and occipital areas.

**Theta Band.** The 3-way ANOVA on frontal sites reported significant effects of condition ($F(1,16)=12.35$, $p=.001$, $\eta_\rho^2=.529$), task ($F(1,11)=17.62$, $p=.001$, $\eta_\rho^2=.616$), block ($F(1,11)=5.99$, $p=.032$, $\eta_\rho^2=.353$), and a significant Condition × Task interaction ($F(2,22)=25.68$, $p<.001$, $\eta_\rho^2=.700$). Frontal theta-band power recorded during the cognitive task in EX+COG and COG was significantly higher than frontal theta-band power during the documentary in EX+DOC (p-values $\leq .02$). In addition, theta-band power was significantly higher during the Stroop task blocks than the 2-back task blocks in both EX+COG and COG, while it remained stable throughout the documentary in EX+DOC. Occipital theta-band power reported a significant main effect of block ($F(1,11)=8.46$, $p=.014$, $\eta_\rho^2=.435$) and task ($F(1,11)=7.96$, $p=.017$, $\eta_\rho^2=.420$) and a significant interaction Task × Block ($F(1,11)=8.90$, $p=.012$, $\eta_\rho^2=.447$). Theta-band power in Oz was greater in the Stroop compared to the 2-back task blocks however it did not differ between conditions. Overall, the cognitive task in EX+COG and COG increased theta-band power compared to the documentary, it also elicited contextual and functional changes in frontal theta-band power associated with the task performed, i.e., the Stroop task induced greater theta activity.

**Alpha Band.** Frontal alpha-band power reported a significant main effect of block ($F(1,11)=10.62$, $p=.008$, $\eta_p^2=.491$) and a significant interaction Condition × Block × Task ($F(2,22)=4.87$, $p=.018$, $\eta_p^2=.307$). Pairwise comparisons between conditions did not report significant difference at any time ($p$-values >0.100). Hence, the effects of task and block were investigated within each condition. COG alpha-band power was significantly higher in the 2-back task compared to Stroop ($F(1,11)=21.01$, $p=.001$, $\eta_p^2=.656$), however it did not change significantly over blocks ($F(1,11)=1.27$, $p=.284$ $\eta_p^2=.103$). Alpha-band power during the documentary increased significantly after the first 10-min block ($p=.021$) and remained stable thereafter ($p$-values >1.000). Lastly, in EX+COG, alpha-band power increased over time across the two tasks ($F(1,11)=5.60$, $p=.037$, $\eta_p^2=.337$), and it was greater in the Stroop task compared to the 2-back task ($F(1,11)=11.17$, $p=.007$, $\eta_p^2=.504$). Alpha-band power in Oz reported a significant Condition × Task interaction ($F(1,15)=4.60$, $p=.038$, $\eta_p^2=.295$), Block × Task ($F(1,11)=7.95$, $p=.017$, $\eta_p^2=.419$) and the triple interaction Condition × Block × Task was close to significance ($F(1,12)=4.10$, $p=.064$, $\eta_p^2=.271$). However, pairwise comparisons did not reveal significant differences between condition at any block (p-values > .100). Although alpha-band Oz power in EX+COG and COG tended to increase in the second blocks across tasks, this effect was significant only for EX+COG, (EX+COG: $F(1,14)=5.54$, $p=.034$, $\eta_p^2=.284$; COG: $F(1,14)=3.13$, $p=.099$, $\eta_p^2=.183$). No other main effects were found for Oz alpha-band power.

## Supplementary Analysis of the TTE Tests

To compare in-task measure of HR and RPE, each TTE test was divided into quartiles (i.e., 25%, 50% and 75% of the total time). For each variable, the value attained at the end of the minute corresponding to the quartile was used for the analysis (see “relative iso-times” Niccolò et al., 2019). The values of the 0% and 100% corresponded to the first full minute and the final rating of each TTE test, respectively. These data were analysed with 3 (condition;

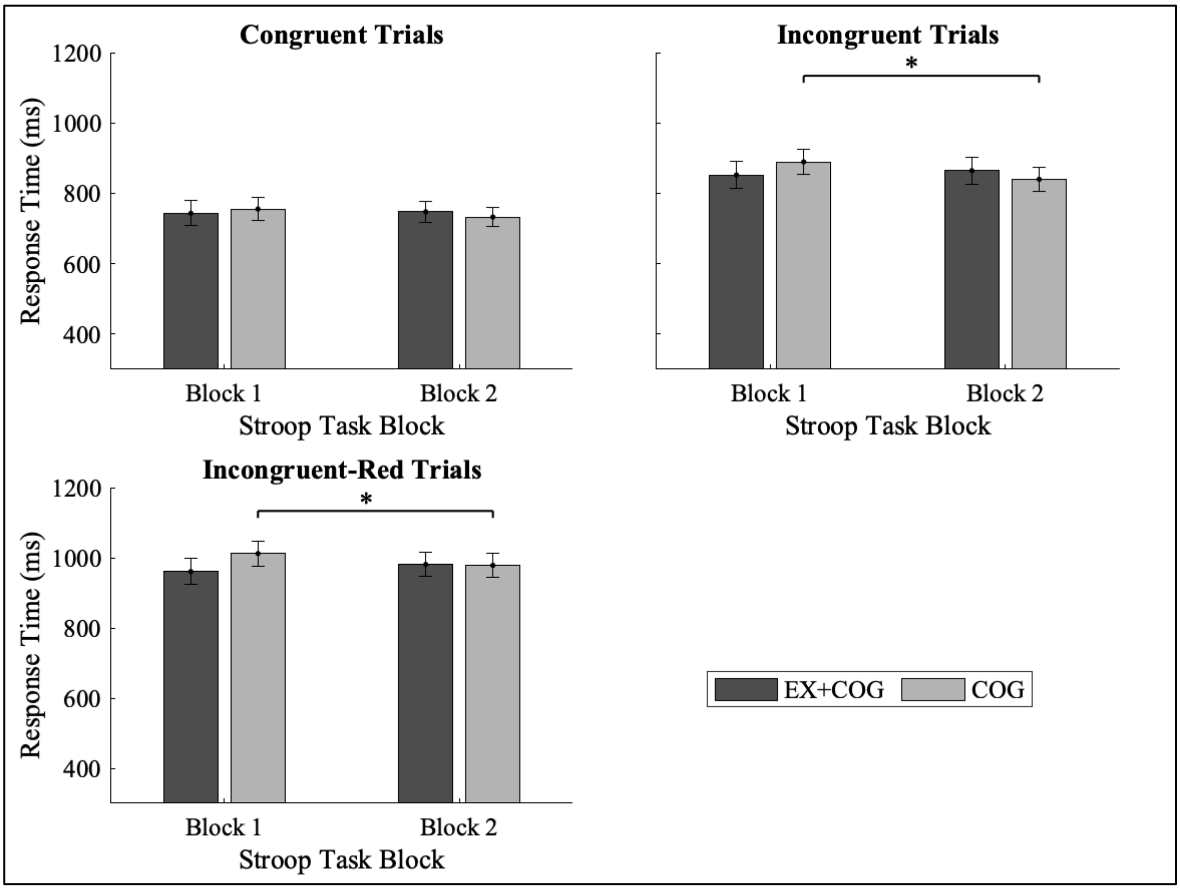
EX+COG, EX+DOC, COG) × 5 %time (1st min and 4 quartiles' minutes of each TTE) repeated measures ANOVAs. In addition, mean cadence during the TTE tests was compared with one-way ANOVA.

### *HR, RPE and Cadence Results*

RPE and HR measured during the TTE tests reported a significant effect of time ($F(2,40)=308.98$, $p<.001$, $\eta_\rho^2=.948$; $F(1,22)=139.67$, $p<.001$, $\eta_\rho^2=.891$, respectively). Both variables increased significantly at each % of time in all conditions. Both, RPE and HR, reported a significant Condition × %Time interaction ($F(4,73)=3.26$, $p=.014$, $\eta_\rho^2=.161$; $F(3,51)=23.03$, $p<.001$,$\eta_\rho^2=.575$, respectively). RPE of the first TTE minute was lower in COG than EX+COG ($p=.008$) and HR was lower in COG than EX+COG ($p<.001$) and EX+DOC ($p<.001$). RPE and HR did not differ between EX+COG and EX+DOC at any point. Average cadence of each TTE test were *M*(*SD*), 82(3), 82(3), and 86(3) rpm in EX+COG, EX+DOC and COG, respectively Cadence was higher in COG compared to EX+COG ($p=.044$) and EX+DOC ($p=.003$) and did not differ significantly between EX+COG and EX+DOC ($p=1.000$).

**Figure S4**

*Response Time for the Stroop Task in EX+COG and COG.*

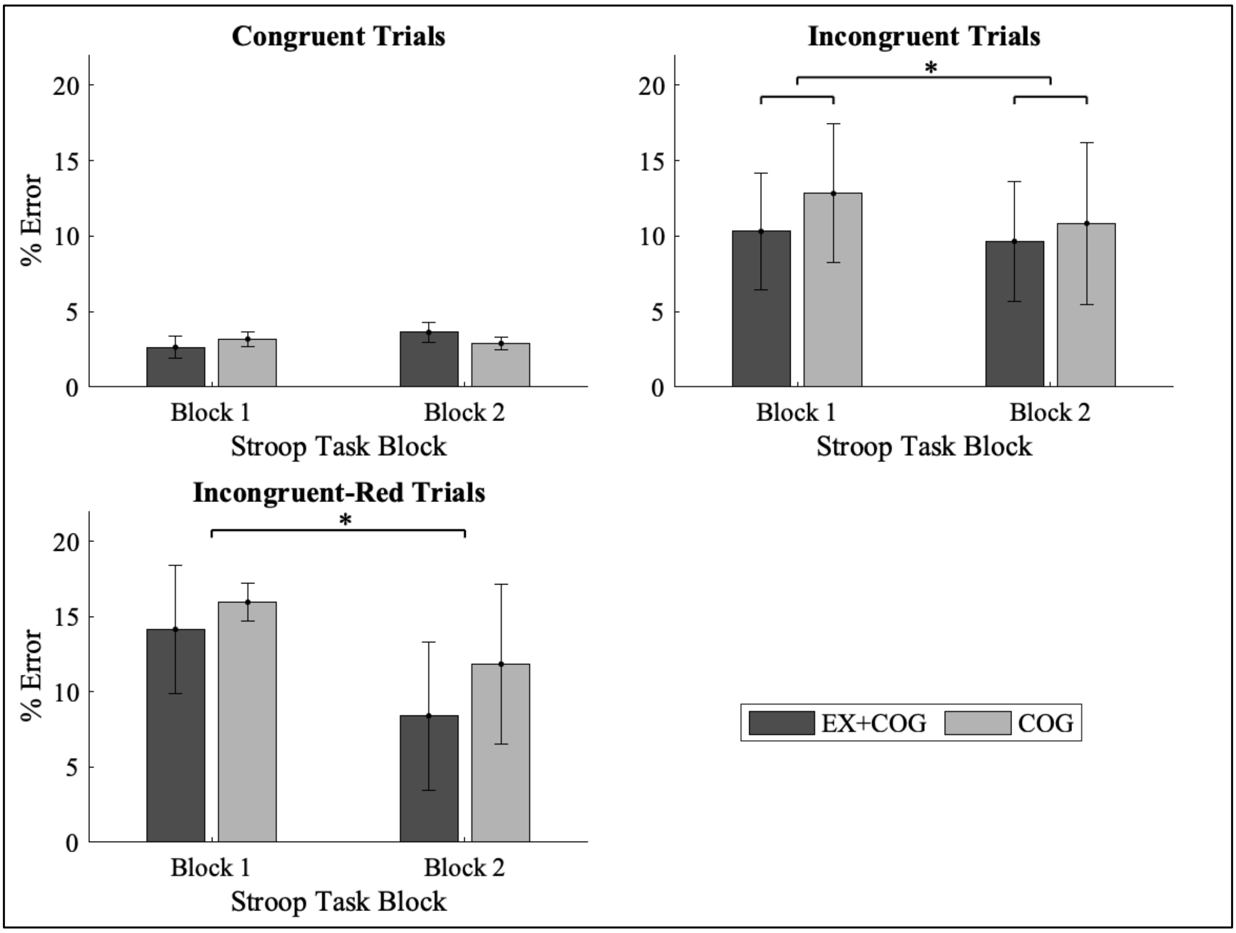


*Note*. Response time, *M*±*SE*, for congruent (upper-left), incongruent (upper-right) and incongruent-red trials (lower-right) of the Stroop task.

* Significant effect of block for COG.

**Figure S5**

*Accuracy (% Error) for the Stroop Task in EX+COG and COG*



*Note*. Response time, *M*±*SE*, for congruent (upper-left), incongruent (upper-right) and incongruent-red (lower-right) trials of the Stroop task.

* Main effect of block across conditions; Lines indicate significant difference between conditions.

# CHAPTER 3

## MENTAL FATIGUE AND POST-EXERCISE RECOVERY: LONGITUDINAL STUDY

## Abstract

**Objectives**: This study adopted an observational approach to investigate the association between mental fatigue and post-exercise recovery measured during the two weeks prior to an important race in a sample of amateur endurance athletes. It was hypothesised that mental fatigue and training load would be negatively associated with post-exercise recovery. **Methods**: 110 participants were recruited among the entrants to an international cycling race. Participants completed a daily questionnaire pack that captured training data (e.g., training duration, perceived effort, muscle soreness) and self-reported measures of mental fatigue, sleep quality, perceived post-exercise recovery, and morning energy and fatigue for the 14 days prior to the event. Anthropometric characteristics and baseline recovery state (Recovery Stress Questionnaire for athletes) were measured before the beginning of daily data collection. These data were analysed via hierarchical linear models. **Results**: The analyses revealed that daily mental fatigue and training load were both negatively associated with perceived post-exercise recovery after controlling for baseline recovery level, muscle soreness and fitness level. Daily mental fatigue and training load also predicted low morning mood state (high fatigue and low energy) after controlling for sleep quality. **Conclusion**: This research adds to the post-exercise recovery literature by identifying mental fatigue as an external psychological factor that undermines athlete's recovery prior to an important race. It is the first study performed in an ecologically valid context to demonstrate the impact of daily mental fatigue on post-exercise recovery.

# Introduction

The balance between training-induced fatigue and post-training recovery is a key factor for endurance performance. Athletes undergo demanding training sessions to achieve their optimal performance (Foster et al., 1996). However, close to an important race, adequate recovery should be prioritized to maintain this performance level (Mujika et al., 2004) with poor recovery associated with disrupted performance and potentially leading to overtraining syndrome (Meeusen et al., 2004). Research has shown that short periods of intensified training in endurance athletes resulted in accumulation of fatigue characterized by decreased performance and self-reported mood disturbances (e.g., Coates et al., 2018; Halson et al., 2002, Kenttä et al., 2006). The energy and fatigue dimensions of mood (from the respective Profile of Mood State subscales, Terry et al., 2003) are particularly affected by training-induced fatigue. In addition to excessive training load, there could be other factors that further undermine post-training recovery. For example, Stults-Kolehmainen & Bartholomew (2012) reported that life stress events and perceived psychological stress influenced recovery of muscular function after resistance training. On a similar line, other researchers indicated that self-reported mental stress disrupted positive adaptations to aerobic training (Ruuska et al., 2012) and psychological stress delayed cortisol recovery after endurance testing (Perna, & McDowell, 1995).

Altogether these findings suggest that both daily training load and psychological stress can lead to an accumulation of fatigue and inadequate post-exercise recovery. However, although a theoretical association between psychological and cognitive stressors and poor post-training recovery has been suggested (e.g., Piacentini & Meeusen, 2015, Kenttä et al., 2001), surprisingly few researchers identify the type of day-to-day psychological and cognitive challenges that could interfere with post-training recovery. The identification and understanding of these psychological and cognitive factors could be particularly relevant for amateur athletes who fit their training sessions in busy schedules. Amateur athletes alternate work, studies and family duties with little or no time to undergo recovery strategies or rest in between these activities. In particular, during their daily routine, these athletes engage in activities that may require effort and expose them to different cognitive demands. Ultimately, these daily activities can elicit mental fatigue (e.g., Aasman et al., 1988; Barker & Nussbaum, 2011; Meijman, 1997). For example, mental fatigue is commonly experienced in the workplace and has been shown to increase over work hours (Johnston et al., 2019; Hülsheger, 2016). Moreover, mental fatigue is generally associated with reduced self-reported vigour (e.g., Craig et al., 2006) and energetic activation (e.g., Trejo et al., 2015) and impaired cognitive performance (e.g., Boksem & Tops, 2006). Mental fatigue is also relevant in the context of endurance performance because prolonged performance of cognitive task immediately before endurance exercise is already known to compromise the performance (Marcora et al., 2009; Van Cutsem et al., 2017). Collectively these findings indicate that daily mental fatigue that is accumulated across daily activities could be one of the psychological factors that undermine post-exercise recovery.

In our previous study, we investigated the effect of mental fatigue on acute post-exercise recovery in a laboratory setting. The study however yielded contradictory results. On the one hand, mental fatigue alone and the intense exercise, both alone and followed by a mentally fatiguing task, significantly and negatively affected some markers of post-exercise recovery. Specifically, the vigour subscale, resource-demand evaluation and perceived recovery declined significantly, and the EEG theta-band power and Flanker task response time increased significantly across the three conditions over the 90-min recovery period. On the other hand, mental fatigue did not have an additive effect to exercise-induced fatigue on these markers. That is, the above markers were not significantly different when the exercise was followed by the mental fatigue manipulation compared to when it was followed by the control manipulation. It was argued that the strenuous exercise before the mental fatigue manipulation elicits great psychological and (neuro)physiological disturbances that could have masked the effect of the mentally fatiguing task. Conversely, the short-term arousing effect of exercise could have initially facilitated the cognitive performance in the mentally fatiguing task and attenuated the effect of mental fatigue on some recovery outcomes (such as vigour, response time) that otherwise would have declined more steeply. The assessment of acute recovery in such a short-time frame provided important details about neurophysiological and psychological disturbances induced by strenuous exercise and cognitively demanding tasks. However, in the context of mental fatigue and post-exercise recovery it has provided only a partial account of our research question as we could not fully determine whether mental fatigue contributes to impaired post-exercise recovery. Hence, further research is required to answer this question.

### The present study

The present research was designed to build on this acute laboratory research by investigating the relationship between daily mental fatigue and post-exercise recovery over a two-week training period that occurred immediately prior to an annual one-day cycling event. This novel cross-sectional approach to investigating the link between mental fatigue and sport performance provides a more ecological "real world" setting for the study of mental fatigue. Furthermore, this approach overcomes the acute, equivocal effect of exercise on the outcomes, thereby allowing us to better understand the relationship between mental fatigue and post-exercise recovery. Recovery state was operationalised using the perceived post-exercise recovery scale (Laurent, 2011). In addition, we assessed two dimensions of morning mood, namely fatigue and energy, as a marker of athletes' fatigue-recovery balance (see Piacentini et al., 2015; O'Connor & Puetz, 2005). As previously mentioned, these two dimensions of mood state should be sensitive to training-induced fatigue (Kenttä et al., 2006) and mental fatigue (Boksem & Tops, 2008). Hierarchical linear modelling was used to test the within-person (day level) and between-person (individual level) effects of mental fatigue and training load on self-reported measures.

### *Study Hypotheses*

The primary hypothesis was that mental fatigue would negatively predict perceived post-exercise recovery at the within-person level and would be negatively associated with morning energy and positively associated with morning fatigue at the within-person level and between-person level. Based on the aforementioned research, it was expected also that training load would be negatively associated with perceived post-exercise recovery at the within-person level and at this level of analysis it would negatively predict morning energy and positively predict morning fatigue.

## Methods

### Participants and Design

This study adopted an observational approach to investigate mental fatigue and recovery around a cycling amateur and international race, Maratona dles Dolomites 2019, that took place on July 7th 2019 in Italy. Participants were recruited among individuals who entered the race and were either Italian or English speakers. The study is part of a larger online data collection including four standard online collection points and daily online collection between the dates of Sunday 23rd June and Saturday 6th July, (i.e., over the 14 days prior to the race). In the present study, only data from the first two online data collection points and the daily questionnaires are displayed because of their exclusive relevance towards the hypotheses of this study. The original sample consisted of 159 participants among which 115 participants completed the daily questionnaire pack throughout the two-weeks that preceded the race. Due to occasional missing answers, the number of individuals retained for analysis was 110 (12 females, 98 males). Before taking part, participants provided written informed consent. The study received local University Ethics Committee approval for testing human participants.

## Procedures

The study was conducted electronically using specialist online data capture software (QualtricsXM). The first online data collection point occurred in June and included a general survey to record anthropometric (e.g., age, sex, weight, height), demographic and training history data along with standard personality traits questionnaires. Table 1 summarised anthropometric and training history data collected at this point. For each participant, Body Mass Index (BMI) was computed from self-reported weight and height and used to estimate maximal oxygen consumption ($\dot{V}O_2max$) based on the equation developed by Jakson et al. (1990), $\dot{V}O_2\,max = 56.36+1.921(PA\text{-}R)-0.381(Age)-0.754\ (BMI)+10.987\ (sex)$ where PA-R = physical activity rating (Jakson et al., 1990). $\dot{V}O_2max$ was then used as an index of athletes' fitness level.

The second data collection point occurred 15 days before the event and captured retrospective baseline details about participants' training sessions, daily routine and activities, recovery and stress for the two weeks preceding this time point (see section *Baseline Data*). Every day thereafter, for 14 days, participants received an email in the morning to ask them to recall and report details about their previous day. These details consisted of daily ratings of physical activity, mental fatigue, post-exercise recovery, sleep quality, and some psychological measures (see section *Daily Questionnaires*).

The questionnaires were presented in English or Italian depending on the chosen language of the participant. All questionnaires and items were originally validated as English-language measures. For participants opting to receive their questionnaires in Italian, we used validated Italian-language translations of the original measures where available. In a few instances where there was no previously validated translation of the English-language measure, the translation to Italian was performed by the lead author.

## Measures

### *Baseline Questionnaires (Saturday 22nd June)*

**Recovery and Stress State.** Firstly, we recorded participants average level of self-report recovery state for the 14 days preceding the daily data collection as a measure of baseline recovery. This was captured with the short version of the recovery and stress questionnaire for athletes (Rest-Q 36 developed by Kellman & Kallus 2001; Nicolas et al., 2019). This short version includes 12 subscales which scores are averaged into four scales that address general stress (*life stress*, *social stress*, *fatigue*), general recovery (*social relaxation*, *general well-being*, *sleep quality*), sport-specific stress (*disturbed breaks*, *emotional exhaustion*, *fitness/injury*) and sport-specific recovery (*fitness/physical shape*, *personal accomplishment*, *self-efficacy*). Each subscale included three items. The Italian version (Di Fronso et al., 2013) was used for the Italian survey. Participants rated how often they experienced the described state on average over the past 14 days on a 6-points scale 0 (*Never*) to 6 (*Always*).

**Baseline Physical Activity Level.** Participants reported the number of cycling training sessions, the average cycling training distance, and the average cycling training time. This was to gather the baseline measures of the average physical activity of the two weeks preceding daily data collection. Descriptive details are reported in Table 1.

### *Daily Questionnaires (Sunday 23rd June – Saturday 6th July)*

The daily data collection started on Sunday 23rd of June with self-report measures relative to Saturday 22nd and lasted for 14 days (i.e., Saturday 6th July which corresponded to the day prior to the race).

**Energy, Fatigue and Sleep Quality**. To keep the daily survey concise, two unipolar scales adapted from the Brunel mood scale (Terry et a., 2003) were used to capture energy and fatigue dimensions of mood. Participants were asked to rate their fatigue ("How fatigue did you feel this morning?") and energy ("How energetic did you feel this morning?") when they woke up on the 5-point Likert scales (1=*Not at all Fatigued/Energetic*, 5=*Extremely Fatigued/Energetic*). The two items were chosen based on the recommendation developed by O'Connor (2004). They also rated the quality of their prior nights' sleep on a 4-point Likert scale, derived from the Pittsburgh Sleep Quality Index (question 6, Buysse et al., 1989).

**Mental Fatigue**. Participants rated the level of mental fatigue experienced during the previous day on a 6-point Likert scale (0 = *Not at all Mentally Fatigued* and 5=*Mentally Exhausted*).

**Perceived Recovery Scale**. Post-exercise recovery was recorded on those days when the individual had trained by asking participants to recall and report how recovered they felt after the respective training session with the perceived recovery scale developed by Laurent (2011).

**Daily Activities**. Firstly, participants were asked whether they had taken part in exercise training on the previous day and if so, training session details were recorded (see below). In addition, they reported their daily activities and duties (e.g., whether they had taken part in work, social, leisure activities, family duties, household, relaxation).

**Training-Diary Data**. On days when participants had trained, they were asked to report training session duration and the rating of perceived effort of the training session. For the session rating of perceived effort, sRPE, participants were asked to rate how was their training session on the 10-point scale (Foster et al., 2001, Foster, 1998). Although the standard practice is to record session RPE within 30 min from the training session (Foster et al., 2001), it has been shown that athletes can accurately recall RPE score up to 48 hours after the training (Phibbs et al., 2017; Scantlebury et al., 2018). Training load was computed by multiplying training duration in minutes by this session RPE score (Foster et al., 2001). Participants also rated muscle soreness on a 10-point scale and reported what time they had started their training session.

### Statistical Analysis

We used hierarchical linear modelling to assess the association between mental fatigue and recovery at day and person level. By accounting for the nested structure of the data, this approach offers an unbiased estimate of parameters and overcome the issue of independent observations, an assumption for multiple regression models (Hoffman & Rovine, 2007). In the current study, the first level of analysis (level 1) includes the daily level predictors, namely the repeated measures of mental fatigue, training load and sleep quality. Day, muscle soreness and training starting time were also included at this level as time-varying control variables. The second level of analysis (level 2) includes the between-person variables, namely the anthropometric characteristic or fitness level ($\dot{V}O_2$max) and baseline recovery state (the four Rest-Q scales). Although $\dot{V}O_2$max is a measure of individuals fitness level because it was estimated from age, sex, BMI and physical activity level, it also accounted for those anthropometric characteristics hence these were not included in the same model. Moreover, daily observations of mental fatigue, training load and sleep quality were aggregated to the person level (i.e., averaged across the 14 days for each individual) and entered in the analysis as between-person predictors. The between-person variables were centred around the grand-mean for the analysis (i.e., the person-mean variable was subtracted from the sample mean). The daily level predictors were centred around each individual' mean (i.e., for each variable, the original individual' daily observation was subtracted from the individual' mean of the variable across the 14 days, see Hoffman & Stawski, 2009). In this way, the time-varying predictors represent the variation about individual's own mean and any between-person variability is removed from their estimates (Hoffman & Stawski, 2009).

**Table 1**

*Descriptive of Sample Characteristics by Sex*

| Variables | | *n* | *M* | *SD* | min | max | TOT (*M*) | TOT (*SD*) |
|---|---|---|---|---|---|---|---|---|
| *Anthropometric Characteristic* | | | | | | | | |
| Age | Female | 12 | 41.83 | 10.50 | 20.00 | 54.00 | 46.15 | 11.07 |
| | Male | 98 | 46.68 | 11.07 | 23.00 | 69.00 | | |
| Weight (Kg) | Female | 12 | 59.62 | 8.99 | 46.50 | 75.00 | 70.57 | 8.20 |
| | Male | 98 | 71.91 | 7.05 | 54.50 | 90.00 | | |
| Height (cm) | Female | 12 | 167.83 | 6.21 | 158.00 | 178.00 | 176.75 | 6.63 |
| | Male | 98 | 177.84 | 5.83 | 165.00 | 195.00 | | |
| Activity Level (PA 0-7) | Female | 12 | 6.83 | 0.39 | 6.00 | 7.00 | 6.85 | 0.58 |
| | Male | 98 | 6.85 | 0.60 | 3.00 | 7.00 | | |
| BMI | Female | 12 | 21.08 | 2.21 | 17.72 | 25.04 | 22.56 | 2.08 |
| | Male | 98 | 22.74 | 2.00 | 17.92 | 28.09 | | |
| *Training History* | | | | | | | | |
| Average cycling session p. week | Female | 12 | 4.25 | 1.71 | 2.00 | 6.00 | 3.98 | 1.45 |
| | Male | 98 | 3.95 | 1.42 | 1.00 | 8.00 | | |
| Average distance p. session (Km) | Female | 12 | 77.50 | 36.21 | 50.00 | 170.00 | 71.48 | 33.80 |
| | Male | 98 | 70.74 | 33.62 | 10.00 | 201.00 | | |
| Years of cycling | Female | 12 | 8.67 | 5.21 | 3.00 | 20.00 | 12.51 | 8.73 |
| | Male | 98 | 12.98 | 8.97 | 1.00 | 40.00 | | |
| *Baseline Training Data* | | | | | | | | |
| Cycling sessions | Female | 12 | 10.00 | 4.59 | 3.00 | 19.00 | 7.72 | 3.15 |
| | Male | 98 | 7.44 | 2.84 | 0.00 | 14.00 | | |
| Cycling time (min) | Female | 12 | 148.75 | 58.63 | 60.00 | 240.00 | 142.55 | 59.86 |
| | Male | 91 | 141.74 | 60.29 | 40.00 | 400.00 | | |
| Cycling distance (Km) | Female | 12 | 52.67 | 17.52 | 30.00 | 80.00 | 80.13 | 106.03 |
| | Male | 98 | 61.91 | 20.79 | 4.00 | 120.00 | | |

*Note*. Baseline training data referred to the training performed over the 2 weeks prior to daily data collection beginning.

# Results

## Hierarchical Linear Model for Perceived Recovery State

This analysis includes 907 observations across participants and days when participants had performed a training session. Table 2 presents the correlations between study variables. In accordance with our first hypothesis mental fatigue was negatively associated with perceived post-exercise recovery following the training session. Before proceeding with the HLM, we investigated whether between- and within-person variance existed in the criterion variables (perceived recovery state) with the null model. In brief, the null model distributes the total variance of each variable into between- and within-person components and the intercept represents the average level of the variable across individual. The procedure revealed 64% of the within-person variability to be explained by perceived post-exercise recovery after training, indicating that HLM was appropriate to use.  We then added to this null model the predictors and random effect and tested the improvement of each nested model above the previous by using the difference in 2×loglikelihood ($\chi^2$ difference test). The first model included fitness level ($\dot{V}O_2max$) and baseline recovery (Rest-Q Scales) at the between-person level and day, training starting time (dummy variable for afternoon and morning training session) and muscle soreness at the within-person level. The final model for perceived recovery state included training starting time, muscle soreness, training load and mental fatigue at the within-person level and fitness level, the Rest-Q sport and general recovery scales, average mental fatigue and average training load at the between-person level. Results of this model are presented in Table 3. At the within-person level mental fatigue was negatively related to perceived recovery such that on average individuals reported lower post-exercise recovery on those days when they also experienced greater mental fatigue. This association persists after controlling for the training load and muscle soreness factors that were also both negatively related to perceived recovery. At the between-person level results showed that individuals who experienced greater mental fatigue across those 14 days also experienced lower post-exercise recovery across the days, though this association did not reach statistical level of significance when controlling for training load, baseline post-exercise recovery state and fitness level (*p*=.072) At this point training load was negatively related to perceived recovery (*p*=.030), while baseline recovery level was positively related to perceived recovery (*p*<.001).

## Hierarchical Linear Model for Mood State

The relationship between mental fatigue and training load on morning energy and fatigue was assessed using the same procedures described above. This analysis included 1440 observations across days and participants. The null model showed that the between-person variance accounted for 28% and 26% of total variance for energy and fatigue respectively. This left 72% and 74% of within-person variance to explain. The first model included anthropometric characteristics along with average sleep quality at the between-person level, and day plus daily sleep quality at the within-person level. Results and predictors of the final models are reported in Table 4. In brief, at the within-person level, mental fatigue and training load were negatively associated with morning energy (*p*-values <.001). On the contrary, at the between-person level, training load was positively associated with energy while mental fatigue still negatively predicted energy, though none reached the statistical level of significance after controlling for individuals' sleep quality. In the final model for fatigue, mental fatigue and training load were positively and significantly associated with morning fatigue at within-person levels. (*p*<.001) Mental fatigue this time was a significant predictor also at the between-person level (*p*<.001).

**Table 2**

*Correlations among Variables*

| Variables | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. MF | 1.00 | -0.01 | 0.01 | -0.12*** | 0.18*** | | | | | | | |
| 2. TL | 0.12 | 1.00 | 0.26*** | -0.18*** | -0.26*** | | | | | | | |
| 3. Muscle soreness | 0.26** | 0.26** | 1.00 | -0.04 | -0.04 | | | | | | | |
| 4. Day | -0.11 | 0.00 | -0.13 | 1.00 | -0.09 | | | | | | | |
| 5. Training start time | -0.05 | -0.12 | -0.07 | -0.03 | 1.00 | | | | | | | |
| 6. Fitness level | 0.20* | 0.08 | -0.06 | -0.24 | 0.10 | 1.00 | | | | | | |
| 7. Age | -0.23* | 0.01 | 0.12 | 0.17 | -0.24* | -0.76*** | 1.00 | | | | | |
| 8. Rest-Q stress general | 0.33*** | 0.00 | 0.24* | -0.21 | 0.05 | 0.09 | -0.17 | 1.00 | | | | |
| 9. Rest-Q rec general | -0.25** | 0.07 | -0.13 | 0.09 | 0.01 | -0.07 | 0.08 | -0.56*** | 1.00 | | | |
| 10. Rest-Q stress sport | 0.06 | -0.04 | 0.23* | -0.02 | -0.01 | 0.06 | -0.05 | 0.43*** | -0.18 | 1.00 | | |
| 11. Rest-Q rec sport | -0.05 | 0.00 | -0.05 | 0.03 | 0.06 | -0.07 | 0.10 | -0.37*** | 0.58*** | -0.35*** | 1.00 | |
| 12. Perceived Recovery | -0.21* | -0.25** | -0.43*** | 0.07 | 0.10 | -0.03 | -0.05 | -0.21* | 0.28** | -0.21** | 0.38*** | 1.00 |

*Note*. Rest-Q = Recovery-Stress Questionnaire scales (general and sport recovery and stress); TL= training load; MF = mental fatigue; Training start time = dummy variable for morning and afternoon. Correlations below the diagonal are person-level correlation with daily measures averaged across the 14 days for each individual (*N*=110). Correlations above the diagonal are daily level correlations (*N*= 907)

****p* <.001, ***p*<.01, **p*<.05.

**Table 3**

*HLM Daily Perceived Recovery Scale*

| | **Perceived Recovery Scale** | | | |
|---|---|---|---|---|
| Variables | *Estimates* | *CI* | | *t* |
| (Intercept) | **6.81***** | 6.50 | 7.12 | 43.44 |
| day | 0.01 | -0.02 | 0.03 | 0.52 |
| Fitness level | 0.02 | -0.02 | 0.06 | 1.03 |
| Rest-Q rec sport | **0.46***** | 0.20 | 0.72 | 3.47 |
| Rest-Q rec general | 0.11 | -0.19 | 0.41 | 0.70 |
| TL day mean | **-0.20*** | -0.37 | -0.02 | -2.19 |
| MF day mean | -0.26 | -0.55 | 0.02 | -1.81 |
| Training start time | -0.18 | -0.45 | 0.09 | -1.33 |
| Muscle soreness daily | **-0.36***** | -0.43 | -0.29 | -10.50 |
| TL daily | **-0.55***** | -0.67 | -0.44 | -9.41 |
| MF daily | **-0.15*** | -0.28 | -0.02 | -2.29 |
| **Random Effects** | | | | |
| Level 1 intercept variance | 2.32 | | | |
| Level 2 intercept variance | 0.98 | | | |
| Variance random effect | 0.14 | | | |

*Note*. *N* observation = 907; *N* id = 110; Rest-Q = Recovery-Stress Questionnaire scales (general and sport recovery); TL= training load; MF = mental fatigue; the two variables were entered at the between-person level (mean across days for each individual) and at the within-person level (daily score deviation from individual mean).

****p* <.001, ***p*<.01, **p*<.05.

**Table 4**

*HLM Daily Morning Energy and Fatigue*

| | **Morning Energy** | | | | **Morning Fatigue** | | | |
|---|---|---|---|---|---|---|---|---|
| Variables | *Estimates* | *CI* | | *t* | *Estimates* | *CI* | | *t* |
| (Intercept) | __2.87***__ | 2.65 | 3.09 | 25.18 | __2.71***__ | 2.46 | 2.99 | 20.11 |
| day | 0.01 | -0.00 | 0.02 | 1.86 | -0.01 | -0.02 | 0.00 | -1.80 |
| Age | 0.00 | -0.01 | 0.01 | 0.28 | 0.01 | -0.00 | 0.02 | 1.97 |
| sex | 0.13 | -0.10 | 0.36 | 1.13 | -0.13 | -0.40 | 0.14 | -0.95 |
| Rest-Q rec sport | __0.13**__ | 0.04 | 0.22 | 2.90 | -0.11 | -0.21 | 0.00 | -1.94 |
| Rest-Q stress general | __-0.20**__ | -0.33 | -0.07 | -2.95 | __0.20**__ | 0.04 | 0.36 | 2.25 |
| Rest-Q rec general | 0.10 | -0.01 | 0.21 | 1.72 | 0.01 | -0.12 | 0.14 | 0.19 |
| Sleep day mean | __0.38__*** | 0.15 | 0.60 | 3.25 | -0.19 | -0.46 | 0.08 | -1.14 |
| TL day mean | 0.05 | -0.02 | 0.13 | 1.45 | 0.03 | -0.06 | 0.12 | 0.71 |
| MF day mean | -0.07 | -0.18 | 0.03 | -1.35 | __0.25***__ | 0.12 | 0.37 | 3.89 |
| Sleep daily | __0.48***__ | 0.42 | 0.54 | 16.27 | __-0.38***__ | -0.44 | -0.32 | -11.98 |
| TL daily | __-0.09***__ | -0.13 | -0.05 | -4.81 | __0.21***__ | 0.17 | 0.25 | 10.43 |
| MF daily | __-0.06***__ | -0.10 | -0.03 | -3.32 | __0.11***__ | 0.07 | 0.14 | 5.26 |
| **Random Effects** | | | | | | | | |
| Level 1 intercept variance | 0.49 | | | | 0.58 | | | |
| Level 2 intercept variance | 0.10 | | | | 0.15 | | | |
| Variance random effect | 0.01 | | | | 0.00 | | | |

*Note*. *N* observation = 1440; *N* id = 110; Rest-Q =Recovery-Stress Questionnaire scales (general recovery, general stress and sport recovery); Sleep = sleep quality; TL= training load; MF = mental fatigue; the three variables were entered at the between-person level (mean across day for each individual) and at the within-person level (daily score deviation from individual mean).

***$p$ <.001, **$p$<.01, *$p$<.05.

## Discussion

The current study adopted a longitudinal cross-sectional approach to investigate the relationship between mental fatigue and post-exercise recovery in a “real world” setting. In accordance with the study hypothesis, at the within-person level mental fatigue was negatively associated with self-reported perceived post-exercise recovery after training. This significant within-person effect of mental fatigue means that on average when the individual experienced greater mental fatigue than usual, he/she also reported lower recovery than usual. This association remained significant after controlling for daily training load and muscle soreness, both significant predictors of low, daily perceived recovery state. Importantly, mental fatigue predicted post-exercise recovery beyond control variables from the between-person level (i.e., fitness level, baseline recovery state and individual average level of mental fatigue).

Altogether, these results showed that daily mental fatigue is an independent predictor of post-exercise perceived recovery in a longitudinal setting. Previous research showed that changes in perceived post-exercise recovery after training were accompanied by changes in subsequent the performance measures (e.g., Cook & Beaven, 2013; Laurent et a., 2011). For example, the first study reported that individual perception of recovery was correlated with sprint performance of the following day (Cook & Beaven, 2013). Moreover, perceived recovery has been reported to be sensitive to strategies used to enhance recovery such as contrast or cold-water immersion (Halson et al., 2008; Stanley et al., 2012). Despite this, few studies have investigated factors that can potentially disrupt perceived post-exercise recovery. Stults-Kolehmainen et al. (2014) showed that high life-event-stress was associated with slow recovery of perceived physical fatigue and muscle soreness in the 96-hr following a resistance training session. From a physiological perspective, Perna and McDowell (1995) also reported that athletes who reported high life-event-stress displayed a delayed cortisol recovery over the 20-hr following an endurance test compared to athletes reporting low life-event-stress. The above research provided evidence for an adverse relationship between post-exercise recovery and non-training, psychological factors. Yet, there are several non-training life stressors that amateur athletes may face throughout their daily routine after training. For example, Piacentini and Meuseen (2015) in a case study of an amateur runner reported that a period of great non-training daily duties resulted in increased overreaching score (a multifactorial score used as warning signal of overtraining syndrome) and mood disturbances in the absence of any training related change. As a consequence, the daily training load of the athlete was reduced to prevent overtraining syndrome. Explicitly investigating such psychological factors is important for assisting athletes to adopt specific strategies to maintain a balance between training and post-exercise recovery. The present finding that daily mental fatigue negatively predicts post-training recovery therefore provides a novel and meaningful addition to this literature.

This study also investigated whether daily training load and mental fatigue predict self-reported morning fatigue and energy. Our results showed that training load contributed to low morning energy and high morning fatigue at a daily level, such that when the individual underwent greater training load than usual, he/she also reported lower energy and greater fatigue in the morning of the next day. Interestingly, training load was positively, yet not significantly, associated with ratings of morning energy at the between-subject level. This is in line with a stream of research showing a positive relationship between vigour and physical activity (see O'Connor & Puetz, 2005). For example, research has shown that individuals who engage in physical activity after work report greater vigour (Ten Brummelhuis & Bakker, 2012). On the other hand, however, the results confirm that at the daily level athletes’ mood state displayed a dose-response relationship with training load (Kenttä et al., 2006). Namely, when training load is increased compared to the individual average level, mood state becomes more negative with ratings of vigour and fatigue displaying greater sensitivity to training-induced fatigue (Kenttä et al., 2006; Meeusen et al., 2013). At this daily level mental fatigue adds to the detrimental effect of training load. Such that, when an individual experienced greater mental fatigue than usual he/she reported lower energy and greater fatigue the morning after. Hence, both daily training load and daily mental fatigue led to morning disturbances in fatigue and energy. It should be noted that the associations remained significant after controlling for sleep quality which is a significant predictor of mood (e.g., Lavidor et al., 2003).

In the previous chapter, it was reported that mental fatigue and exercise contributed to increasing the power within the low frequency bands of the EEG signal (i.e., alpha and theta band) suggesting that this increment could be a neurophysiological marker of fatigue across different types of task. However, the study did not find a specific effect of mental fatigue on markers of acute recovery (i.e., perceived recovery, energy and fatigue). The current study expands these previous results showing that mental fatigue and training load have an independent and significant effect on post-exercise perceived recovery and morning energy and fatigue in a chronic ecologically valid setting. Interestingly, Stults-Kolehmainen et al. (2014) found a significant moderating effect of life stress events on recovery trajectory of self-reported energy and fatigue assessed over the 96-hours following a single session of resistance training. In contrast, when the same research group investigated the variables over 1 hr of recovery, they did not find significant moderations of life stress event on the self-reported measures (Stults-Kolehmainen & Bartholomew, 2012). Consistently with the results of this author, together the findings of this observational study and the experimental study on post-exercise recovery and mental fatigue suggest that self-reported measures of recovery may display a ceiling or floor effect in the first period of recovery. That is, energy and fatigue did not increase/decrease further within the 90 min after a strenuous exercise when the mentally fatiguing task was introduced. However, both training load and mental fatigue predicted these measures when recorded over 24 hr.

From an applied perspective the present results suggest that daily mental fatigue can be detrimental for post-training recovery in a longitudinal setting. Because amateur athletes have to face daily duties that may increase mental fatigue, coaches working with these athletes should consider the mental fatigue that may arise from an athletes' daily obligations when programming training sessions. In particular, because both training load and mental fatigue induced energy and fatigue disturbances the day after training, athletes may prioritize intense and/or long training sessions around days when they can rest afterwards and should limit this type of sessions when high cognitive demands are unavoidable. Overall, the current results support the use of mood state for daily general monitoring of amateur athletes as it is sensitive to both training load and daily cognitive demands. However, coaches should be mindful that this measure is not specific if one wants to assess training-related responses.

## Limitations and Future Directions

In sport literature, research on mental fatigue so far has used an empirical approach, implementing prolonged computerised tasks to induce a state of mental fatigue. While a laboratory setting allows tighter control of extraneous variables and can establish a cause-and-effect relationship between variables, there is a growing need to translate the findings on mental fatigue into a more ecologically valid setting (Van Cutsem et al., 2017). As such, the present study is the first to assess mental fatigue encountered by athletes during specified daily period in the lead up to a race. This approach, however, is not without limitations. Firstly, self-report measures results could be biased in terms of social desirability. They are also subject to recall error based on retrospective recall nature of sampling. The within-person analysis should have reduced any impact of systematic recall bias. However, the inclusion of physiological indices of post-exercise recovery such as heart rate variability is recommended to overcome other bias-risks inherent in self-report measures. The addition of physiological measures could be a major addition to future research. Furthermore, the analysis included in the present study was limited to the association between mental fatigue and post-exercise recovery, since a stable relationship between these two variables needed to be established before testing mediators and moderators. To build on the current results, future research can use this study as a foundation to test mediation and moderation hypotheses. For example, research should test any moderating effect of mental fatigue on the training load and recovery relationship. Similarly, the subjective experience and motives of the training sessions, as well as the daily activities, could respectively moderate the effect of daily training load and daily mental fatigue on post-exercise recovery. Moreover, it is possible that occupations or specific activities differently affect the relationship between mental fatigue and recovery. Specific vocational roles and their impact on mental fatigue and post-exercise recovery therefore warrant specific focus in future research.

## Conclusion

This is the first study to investigate the effect of daily mental fatigue on the post-exercise recovery of athletes in an ecological setting. The findings show that daily and average mental fatigue is negatively associated with athletes perceived post-exercise recovery. Also, mental fatigue and training load independently predicted morning energy and fatigue throughout the 14 days prior to an important event. Overall, the study showed that mental fatigue could impede adequate post-exercise recovery and amateur athletes should therefore consider their daily cognitive demands when planning their training sessions.  Moreover, our results encourage the use of daily mood assessment as a comprehensive measure of overall fatigue and recovery balance in master athletes.

# CHAPTER 4

## EEG-NEUROFEEDBACK IMPROVES CYCLING TIME-TO-EXHAUSTION

# Abstract

**Objective:** The role of the brain in endurance performance is frequently debated; surprisingly, few investigations have attempted to improve endurance performance by directly targeting brain activity. One promising but untested approach to modifying brain activity is electroencephalogram (EEG) neurofeedback. Consequently, our experiment is the first to examine an EEG neurofeedback intervention for whole-body endurance performance. **Method:** We adopted a two-part experiment. The first consisted of a randomized parallel controlled design. Forty participants were allocated to three experimental groups; increase relative left cortical activity (NFL), increase relative right (NFR), and passive control (CON). They performed a depleting cognitive task, followed by either six 2-min blocks of EEG neurofeedback training (NFL or NFR) or time-matched videos of the neurofeedback display (CON). Next, they performed a time-to-exhaustion (TTE) test on a cycle-ergometer. We then tested participants of NFL and NFR groups in an additional experimental visit and administered the opposite neurofeedback training within a fully repeated-measures protocol. **Results:** EEG neurofeedback modified brain activity as expected. As hypothesized, the NFL group cycled for over 30% longer than the other groups in the parallel controlled design, NFL: 1382 ± 252 s, NFR: 878 ± 167, CON: 963 ± 117 s. We replicated this result in the repeated-measures design where NFL: 1167 ± 831 s performed 11% longer than NFR: 1049 ± 638 s). There were no differences in pre-exercise fatigue, vigour or self-control; area under the curve group-differences for perceived effort were interpreted within a goal persistence framework. **Conclusion:** The brief EEG neurofeedback intervention elicited greater relative left frontal cortical activity and enhanced endurance exercise performance.

## Introduction

The role of the brain in endurance exercise performance has been debated for a number of years. During this time, however, surprisingly few investigations have attempted to alter endurance performance by directly targeting brain activity (Angius et al., 2018). One novel approach to directly modifying brain activity is electroencephalogram (EEG) neurofeedback. Neurofeedback is a non-invasive technique based on operant conditioning whereby individuals learn to self-regulate their electrocortical activity with the aid of positive reinforcements whenever electrocortical activity meets a pre-designated pattern (Enriquez-Geppert et al., 2017). Accordingly, neurofeedback provides an exciting opportunity to train individuals to produce brain activation patterns that might be conducive for endurance performance, and thereby yield a new non-invasive intervention to enhance endurance performance. This technique could also shed important new light on brain and endurance performance mechanisms. This paper reports on the first investigation of these pressing issues.

### EEG-Neurofeedback

The EEG assesses cerebral activity via electrodes attached to the scalp to record voltages emitted from the brain. This signal is dominated by oscillations that are usually decomposed into five characteristic frequencies [delta (0.5–3.5 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta (13–30 Hz), and gamma (30-80 Hz)] reflecting specific brain states and cognitive functions (Knyazev, 2007). Slow frequencies within the delta-band are prevalent during deep sleep, theta-band has been associated with different cognitive functions like encoding information, alpha-band reflects suppressed brain activity, and it has been associated with resting states, inhibition of cortical activity and directed attention, while faster frequencies (e.g., beta-band) are associated with alertness and attention (see Engel & Fries, 2010; Knyazev, 2007). In a typical EEG-neurofeedback session, the EEG signal is recorded from the scalp and computer software extracts the EEG feature that is the target of the neurofeedback training (e.g., spectral power in the alpha frequency band). This EEG feature is then compared to a criterion (e.g., a pre-defined target alpha power level) and displayed back via visual and/or auditory stimuli (e.g., graphs on a computer screen; an auditory tone). In this way, performers receive instantaneous, real-time feedback that indicates the current activity of the selected brainwave compared to the desired level of activation, hence they can begin to develop strategies to control their brainwaves to match the pre-defined target level (Enriquez-Geppert et al., 2017).

Research has used EEG-neurofeedback training to enhance cognitive performance (Gruzelier, 2014) and, more recently, neurofeedback has been utilized with self-paced target sports (e.g., Ring et al., 2015) as studies have reported cortical signatures that appear to characterise optimal performance during the final moments of motor preparation for such tasks (Cooke et al., 2014). However, compared to fine-motor skills (e.g., golf putting), whole-body exercise presents methodological hurdles such as muscular artefacts, electrode movement and sweat (Perrey & Besson, 2018), which make it difficult to discern brainwaves that characterize superior performance for data-driven neurofeedback interventions. To tackle this issue, we have advocated a prescription approach that allows the development of theory-driven neurofeedback protocols in the absence of prior data (Cooke et al., 2018). In the present study, we developed and tested a prescription for neurofeedback to enhance endurance performance, drawn from the approach-withdrawal model of frontal asymmetry (Davidson, 1992) alongside the psychobiological model of endurance performance (Marcora, 2008).

## The Brain and Endurance Performance

According to the psychobiological model of endurance performance, exercise capacity is a goal-directed behaviour that is limited by a conscious decision to withdraw from exercise when the effort is perceived as no longer possible or justified (Marcora, 2008). During endurance events, athletes face increasingly unpleasant physical sensations, such as fatigue, pain and discomfort (McCormick et al., 2018). In this context, the motivation to continue, despite the rising urge to quit, is pivotal (Schiphof-Godart et al., 2018). The psychobiological model of endurance performance therefore predicts that any intervention that reduces the perception of effort will improve endurance performance (Blanchfield et al., 2014).

According to the approach-withdrawal model of frontal asymmetry (Davidson, 1992; Harmon-Jones & Gable, 2018), lateralization of brain activity across the prefrontal cortical hemispheres reflects opposite motivational directions that drive behaviours and emotions. Left-sided frontal activity is associated with approach-related processes whereas right-sided frontal activity is associated with avoidance-related processes (Harmon-Jones & Gable, 2018). EEG research has measured asymmetric frontal cortical activity by subtracting alpha power at the left frontal leads from alpha power at the right leads (i.e., relative frontal alpha asymmetry). Power within the alpha frequency band (8-13 Hz) is *inversely* related to cortical activity. Hence, positive values are indicative of greater left over right frontal cortical activity, while negative values indicate a greater right over left frontal cortical activity (Smith et al., 2017). Using this asymmetric index, previous studies reported that relative left frontal cortical activation is associated with positive affective responses to appetitive stimuli (Harmon-Jones & Gable, 2009) and action motivation (Berkman & Lieberman, 2010). More importantly, experimentally manipulated changes in relative left over right frontal cortical activity led to increased persistence during an unsolvable cognitive task (Schiff et al., 1998) and an action-orientated mindset (Harmon-Jones et al., 2008). These findings collectively suggest that relative left frontal cortical activity initiates motivational and cognitive processes that favour the maintenance of performance, especially when effort is at its highest. Pertinently, Allen et al. (2001) demonstrated that EEG-neurofeedback can be used to modify relative frontal alpha asymmetry. In their study, individuals were trained to increase either relative right or relative left frontal cortical activity with five 6-minute sessions of neurofeedback performed over five consecutive days. They found that the group trained to increase relative left frontal cortical activity reported significantly more amusement, interest, and happiness in response to a film and significantly more zygomatic activity (‘smile’ faces) than the group trained to increase relative right frontal cortical activity. Similar effects have been reported by more recent studies (e.g., Peeters et al., 2014; Quaedflieg et al., 2016) with Peeters et al. reporting that just a single session of neurofeedback effectively modified relative frontal alpha asymmetry. However, these studies primarily focused on the effect of neurofeedback training for asymmetric frontal cortical activity on affective responses, whereas behavioural outcomes received little attention. Behavioural outcomes are central, however, in endurance events.

### Aim of the Present Experiment

The present research is the first to test the use of neurofeedback as a brain-based intervention to improve endurance exercise performance; specifically, the effect of increased relative left frontal cortical activity on whole-body endurance performance. We implemented a two-part experiment; the first involved a between-subject design, while in the second part the same group of participants was tested in a fully repeated measures design. Based on the aforementioned research, we reasoned that an alpha asymmetry neurofeedback protocol designed to increase relative left frontal cortical activity would enhance approach motivation and delay the urge to withdraw that is thought to terminate endurance exercise. We also anticipated that the intervention could be especially useful when participants are already in a state of cognitive depletion and fatigue prior to the start of endurance exercise. This is because a state of cognitive depletion is thought to elevate perceived effort and impair subsequent endurance exercise (e.g., Bray et al., 2008). Accordingly, we manipulated individuals’ asymmetric frontal activity after they engaged in an effortful, depleting cognitive task used to exacerbate the feelings of fatigue (Inzlicht & Berkman, 2015). We then assessed the effect of our frontal asymmetry neurofeedback protocol on performance and perception of effort (i.e., RPE) during a cycling time-to-exhaustion test. On the basis of the approach-withdrawal motivational model of asymmetric frontal activity (Harmon-Jones & Gable, 2018) that we adopted to prescribe the neurofeedback interventions, we hypothesized that increased relative left frontal cortical activity would allow individuals to cycle for longer during a constant load time-to-exhaustion task compared to both the opposite neurofeedback intervention (increased relative right frontal cortical activity) and a passive control intervention. Based on the psychobiological model of endurance performance (Marcora, 2008), we further expected that neurofeedback-induced performance differences would be characterized by reduced perception of effort.

## Experiment 1A: Between-Subject Design

## Methods

### Participants

Forty volunteers (*n* = 26 males and *n* = 14 females) between 18 and 45 years old were recruited from university and local sports clubs.  The sample was informed by power analysis based on previous research illustrating the effect of neurofeedback on alpha asymmetry. Research by Quaedflieg et al. (2016) and Mennella et al. (2014) reported that EEG-neurofeedback protocols such as the one used in this experiment elicited a significant and medium effect size ($\eta^2_p = 0.08$ and $\eta^2_p = 0.14$, respectively). Using the average of these effect sizes, GPower indicated that a sample of 27 participants would be sufficient to detect a comparable effect via the between-subject factorial ANOVA design that we planned to employ [($f = 0.33$), $\alpha = 0.05$, and $\beta = 0.80$)]. Accordingly, by recruiting a sample of 40, we were more than sufficiently powered to detect the expected effect.

In order to participate in this research, participants had to be free from self-reported illness, injury and dyslexia, and not taking medication except the contraceptive pill. Participants were asked to sleep at least seven hours, avoid heavy exercise and alcohol during the 24 hours preceding each experimental visit, to avoid nicotine and caffeine for three hours before each experimental visit, and to consume a light meal two hours before attending each visit. Compliance with these instructions was confirmed at the start of each visit. All participants provided written informed consent and the study was approved by the Research Ethics Committee according to the Declaration of Helsinki.

### Design and Experimental Procedures

We adopted a randomised between-groups design to investigate the effect of EEG-neurofeedback on exhaustive endurance exercise performance. Participants were randomly allocated to either an increase relative left frontal cortical activity neurofeedback group (NFL group), or one of two control groups: an increase relative right frontal cortical activity neurofeedback group (NFR group), or a no-neurofeedback passive control group (CON group). After receiving the neurofeedback intervention, or the passive control intervention, all participants completed a time-to-exhaustion exercise test on a cycle ergometer.

Participants made two laboratory visits, separated by a minimum of 48 hours, and a maximum of 14 days. Laboratory conditions were standardized *M*(*SD*) at a temperature of 20 (1) ºC, atmospheric pressure of 1015 (9) mbar, and humidity of 53 (7)%.

**Visit 1.** The first session was identical for all three groups and involved a maximal incremental ramp test on a cycle-ergometer (Excalibur Sport, Lode, Groningen, Netherlands) to assess individuals' maximal oxygen consumption ($\dot{V}O_2max$) and peak power output (PPO). Before the test, anthropometric measurements (body mass and height) were recorded. The ramp test started with 2 min rest after which the power automatically increased from 50 W by 25 W every minute until voluntary exhaustion. Verbal encouragement was provided close to the end of the test to ensure that participants reached their maximal effort. During the maximal incremental test, oxygen consumption was measured breath by breath via a computerized metabolic gas analyser (Metalyzer 3B, Cortex Biophysik, Leipzig, Germany) connected to a mouth mask (7600 series, Hans Rudolph, Kansas City, MO, USA). The device was calibrated before each test using a known concentration of gases and a 3L calibration syringe (Series 5530, Hans Rudolph). Maximal oxygen consumption was defined as the highest value of oxygen uptake averaged over 15 s. Heart rate (HR) was recorded continuously throughout the test with a wireless chest strap (S610, Polar Electro, Kempele, Finland) and rating of perceived effort (RPE) was measured at the end of every incremental stage using the Category Ratio scale (CR-10) developed by Borg (1998). The standard instructions of the scale were provided to participants prior to starting the test and low and high anchor points were established using the procedures advocated by Noble and Robertson (1996). This first visit allowed participants to familiarize with the laboratory setting and testing procedures that were used for the experimental trial.

All exercise tests were performed on the same braked cycle-ergometer (Excalibur Sport, Lode, Groningen, Netherlands) set in hyperbolic mode, which allows the power to change independently of pedal frequency. For all exercise tests, exhaustion was defined as the point at which the individual voluntarily stopped the test, or the cadence had fallen below 60 revolutions per minute (rpm) for more than five consecutive seconds. During the tests, participants were asked to remain in the saddle and were allowed to freely choose their cadence so long as it remained between 60 and 100 rpm.

**Visit 2.** Upon arrival, all participants were briefed about the visit and then prepared for the EEG recording (see details below). The procedure took 20 min after which the Brunel Mood State Scale (BRUMS) and the State of Self-Control Capacity Scale (SSCCS) were administered (see section on psychological measures). All participants then completed a brief writing task designed to elicit a state of mild cognitive depletion and fatigue (see section on written task) followed by a second assessment of mood (BRUMS) and self-control (SSCCS). They then received an EEG-neurofeedback intervention (NFL or NFR) or a time-matched viewing of

EEG signals without actively controlling them (CON) followed by a final assessment of self-reported mood and self-control. Next, participants moved onto the cycle-ergometer to perform a time-to-exhaustion cycling test, which required them to pedal for as long as possible at an intensity of 65% of their peak power output (see section on cycling time-to-exhaustion test, TTE).

## Manipulations and Measures

**Written Task (WT).** Before the neurofeedback/control interventions, all participants were instructed to produce a handwritten copy of a typed piece of text consisting of 336 words (one page) describing physics processes. Importantly, they were asked to omit the letters *A* and *N* from every word when producing their handwritten copy. This meant that the performer had to override their automatic writing habits so as to comply with the instructions of the written task. This task was adapted from similar versions previously used successfully to induce a state of mild cognitive depletion (Myers et al., 2018). The same text was used for all individuals and the time taken to complete the writing task was recorded. In each visit 30 min elapsed between the completion of the written task and the start of the TTE tests.

**EEG Recording.** EEG signal was recorded from F3 and F4 sites on the scalp using Ag/AgCl electrodes (Blue Sensor SP, Ambu) connected to a DC amplifier (PET-4, Brainquiry, neuroCare Group) that digitalised the signal at 1000 Hz. The active electrodes were positioned with a stretchable lycra cap in accordance with the 10-20 system (Jasper, 1958) and were referenced to linked mastoids, with a ground electrode positioned at FPz. The recording sites were abraded using a blunt needle and a conductive gel was applied, while an abrasive cream (Nuprep, Weaver and Company) and alcohol wipes were used to clean the mastoids and the forehead, before electrodes were attached. Electrode impedance at each site was kept below 10 kΩ. Before completing the written task, five 5 s baseline recordings were taken while participants sat still and maintained their gaze toward a black fixation cross printed on a white background. The power within the alpha frequency band (8-13 Hz) was averaged over the five baseline recordings and across the two sites, F3 and F4, and the value was used to individualise the thresholds for the neurofeedback interventions.

**EEG-Neurofeedback Interventions (NFL and NFR Groups).** The neurofeedback interventions consisted of six blocks of two minutes with one minute of rest in between each block. During each block, a computer running Bioexplorer software (Cyberevolution, Brainquiry, neuroCare Group) extracted the signal from each lead and simultaneously calculated the alpha frequency power using a fast Fourier transform algorithm with Hanning windowing function. The signal was 8-13 Hz band-pass filtered using the 6th order Butterworth IIR filter and averaged continuously every 5 ms. The resulting values were then displayed to participants on-screen via bar charts displaying alpha power at the F3 and F4 sites and an auditory tone that changed in pitch with changes in the ratio of F3 and F4 alpha power.

***NFL Group.*** Importantly, for members of the NFL group, the tone was set to silence and the colour of the bar changed from red to blue when participants decreased their F3 alpha power by 1.5% and increased their F4 alpha power by 1.5% from their baseline level (blocks 1-3), or when they decreased F3 by 3% and increased F4 by 3% (blocks 4-6). Participants were told that decreasing the height of the F3 bar and increasing the height of the F4 bar would silence the tone and that their goal was to silence and keep it silent for as long as possible.

***NFR Group***. The procedure for the NFR group was identical except that their goal was to increase the height of the F3 bar and decrease the height of the F4 bar. The tone silenced when they increased their F3 alpha power and decreased their F4 alpha power from baseline by 1.5% (blocks 1-3) and 3% (blocks 4-6). To help ensure the signal was being regulated by cognitive processes and was not contaminated by artifacts, the tone was prevented from silencing in both the NFL and the NFR interventions during any periods where there was > 10-µV of 50 Hz activity in the EEG signal.

**Passive Control Group**. Participants in the passive control group underwent the same procedures as the other groups (i.e., EEG set up, baseline assessment, and written task); however, instead of receiving the neurofeedback training, they watched six 2-min video clips displaying a replay of the neurofeedback session from random participants in the experimental groups (3 from the NFL and 3 from NFR group, ordered randomly and then presented to all participants in a standardized sequence). This ensured that members of the passive control group were exposed to the same auditory and visual stimuli as members of both experimental groups. The passive control group were not given any instructions about controlling the bars on the screen, they were instead told that they were to watch a video of a neurofeedback recording while sitting still and remaining silent.

**Cycling Time-to-Exhaustion (TTE) Test.** After the neurofeedback intervention, participants performed a TTE on the cycle ergometer. The test started with a 3-min warm-up with the intensity set at 30% of individuals' PPO. After the warm-up, the intensity was increased automatically to a power output corresponding to 65% PPO and participants were instructed to cycle for as long as they could. Before starting the test, participants were reminded to cycle until exhaustion, to remain sitting in the saddle for the duration of the TTE test and to maintain the cadence between 60 and 110 rpm. No verbal encouragement, or feedback about elapsed cycling time, were provided at any point during any cycling TTE.

HR was recorded continuously throughout the TTE using the Polar HR monitor (Polar RS800CX, Polar Electro, Kempele, Finland). HR value in the final 15 s of each minute was recorded and used for analysis. RPE was evaluated using the CR-10 scale (Noble & Robertson, 1996) presented to participants at the final 15 s of every minute of the TTE test. Participants were instructed to rate how hard, heavy and strenuous the cycling TTE test felt at that moment (Marcora, 2010). Three minutes after the end of the TTE test, a 0.5 µl sample of whole fresh blood was taken from the left earlobe and blood lactate concentration was measured with a portable lactate meter (Lactate Pro 2 LT-1730, Arkray, Shiga, Japan).

**Psychological Questionnaires.** Upon their arrival (baseline), after the written task and after the interventions, participants completed the following questionnaires:

***Brunel Mood Scale (BRUMS).*** Mood state was recorded using the BRUMS (Terry et al., 2003). The scale includes 24 items divided into six subscales (depression, fatigue, vigour, tension, confusion, anger). Participants were instructed to indicate the extent to which they were experiencing the feeling described by the item at that moment in time ("how do you feel right now") using a 5-point scale (0 = *not at all* to 4 = *extremely*). A total score for each subscale was computed by summing the ratings of its respective items. For the purpose of this experiment, we were interested in ratings of fatigue and vigour, and focused our analyses on these subscales.

***State Self-Control Capacity Scale (SSCCS).*** The SSCCS developed by Ciarocco et al. (2004) was used to assess participants' momentary state of self-control. The scale included 26 items (e.g., "I feel sharp and focused") rated on a 7-point Likert-type scale from 1 (*not true*) to 7 (*very true*). Higher values were representative of a greater state of self-control (no depletion) while lower values indicated a greater state of depletion.

## Data Reduction

**EEG.** Matlab (R2017b) was used to extract EEG data recorded during the neurofeedback and control interventions for statistical analyses. The signal from F3 and F4 was down-sampled offline at 256 Hz, and a 1 Hz high pass filter (cut off frequency 0.8 Hz and transition bandwidth 0.4 Hz), and 30 Hz low pass filter (cut off frequency 35 Hz and transition bandwidth 10 Hz), were applied. Continuous EEG data were manually corrected for eye blinks artefacts. Each 2-min block was divided into 2 s epochs (75% overlap) and epochs containing artefacts greater than ± 75 μV were rejected. The power spectrum was derived from each retained epoch by a fast Fourier transformation with a 100% Hanning windowing (spectral resolution of 0.5 Hz). For each NF block, power within the alpha frequency (8-13 Hz) was averaged across epochs and the resulting values used to compute the index of alpha asymmetry defined as the log-transformed alpha power at F4 minus the log-transformed alpha power at F3 (Ln [alphaF3] – Ln [alpha F4] (Smith et al., 2017).

**HR and RPE.** To give insight into the temporal changes of RPE and HR throughout the cycling TTE test, we split each participant's TTE test into five time-points; the first time-point corresponded to the end of the first minute of the test, the last four time points corresponded to the 25%, 50%, 75% and 100% of the individual's total cycling time. For each individual TTE test, the values of HR and RPE attained at the minutes corresponding to the 5 time-points were used for the analysis. To provide further insight into the time-responses of these two variables, we computed the area under the curve (AUC) for RPE and HR using the integrated trapezoid formula (Pruessner et al., 2003). For each individual TTE test, the trapezoid areas were calculated from the values of HR and RPE attained at the minutes corresponding to the 25%, 50%, 75%, 100% of the total time to exhaustion test and the time distance between these points,

e.g., $AUC_{RPE} = (RPE_i + RPE_{i+1}) \cdot {}^{t_i}/_{2}$

where $i$ = height at the start of the quartile, $i+1$ = height at the end of the quartile, and $t_i$ = duration (length) of the quartile (Pruessner et al., 2003).

### Statistical Analysis

**Main Analyses**. We performed a 3 (Group) × 6 (Block) mixed-model ANOVA to assess the effectiveness of the neurofeedback intervention in manipulating frontal asymmetry. We ran planned orthogonal contrasts to compare the TTE achieved by participates in the NFL group with the TTE achieved by participants in the NFR (a form of active control) and CON (passive control) groups. Finally, 3 (Group) × 5 (Time) ANOVAs were used to examine the effects of neurofeedback on HR and RPE during the cycling TTE test. Planned orthogonal contrasts were used to compare the AUCs for RPE and HR.

**Control Analyses.** We also performed a number of control analyses. First, to check that our random assignment was successful in balancing the groups at baseline, we subjected fitness levels, anthropometric characteristics, baseline alpha-asymmetry, fatigue, vigour and self-control to one-way between-group ANOVAs. Second, to ensure that our written task and our neurofeedback interventions had a similar effect on the self-control, fatigue and vigour of participants, we tested these self-report measures with 3 (Group) × 3 (Time; baseline, post-written task, post neurofeedback) ANOVAs. Finally, to check that all participants reached a similar level of exhaustion at the end of each TTE test, mean cadence, RPE at exhaustion, HR at exhaustion, and blood lactate at exhaustion were analysed with one-way between group ANOVAs. In all cases the assumptions of homoscedasticity and sphericity were tested with Levene and Mauchly tests and results were reported with the appropriate corrections (Welch's F and Greenhouse–Geisser correction) applied when the assumptions had not been met. The nonparametric Kruskal-Wallis test was used on data that did not meet the assumption of normality as assessed with the Shapiro-Wilk test. Significant interactions were investigated with planned contrasts. For all analyses, statistical significance was set at $p \leq 0.05$ and the effect sizes were reported as partial eta squared ($\eta_p^2$) and Hedges's $g_s$ (Lakens, 2013).

## Results

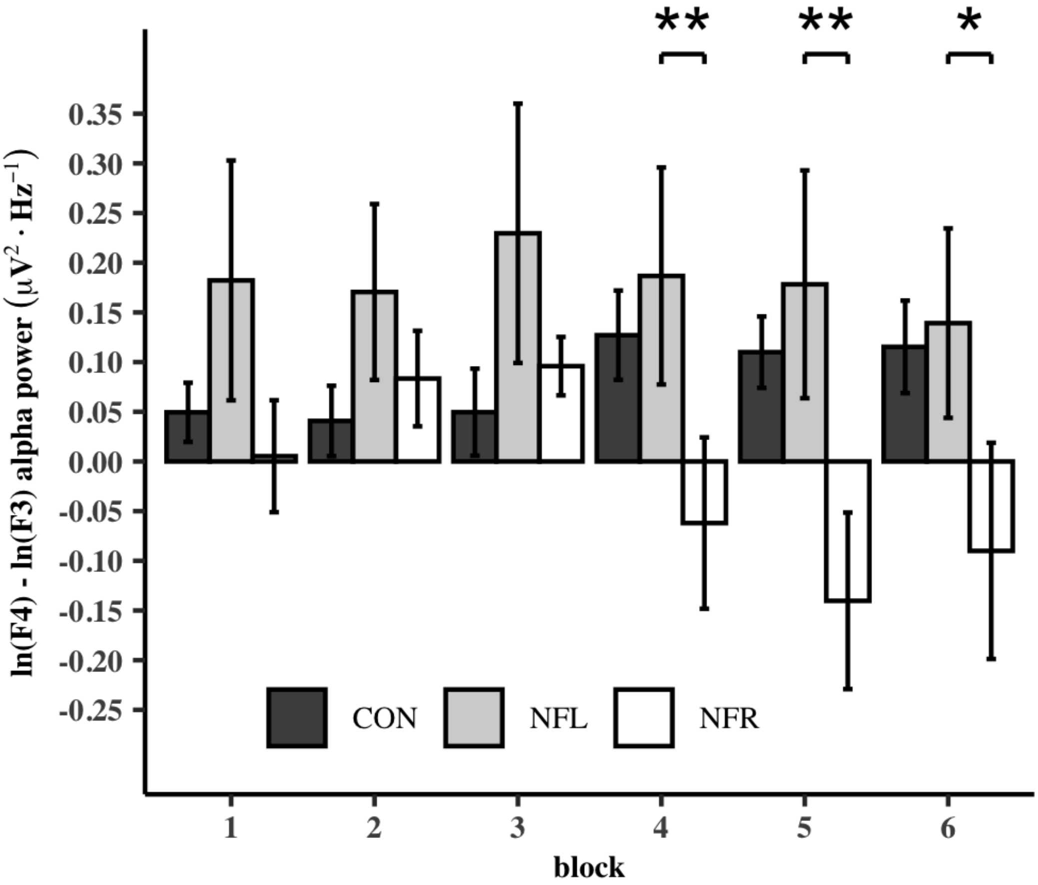
### Alpha asymmetry

The 3 (Group) × 6 (Block) ANOVA on the alpha asymmetry indices revealed a significant interaction ($F(6,116)=2.29$, $p=.038$, $\eta_p^2=.11$). Post-hoc planned contrasts revealed a significant difference in alpha asymmetry between the NFL and NFR groups in blocks 4 ($t(37)=2.10$, $p=.043$, $g_s=.65$), and 5 ($t(37)=2.64$, $p=.012$, $g_s=.82$). Accordingly, alpha asymmetry scores in the two active groups diverged as the intervention progressed, with the

NFL group manifesting more left-sided frontal cortical activity, and the NFR group more right-sided frontal cortical activity in the last three blocks of the neurofeedback intervention. This indicates that our neurofeedback intervention was successful in establishing two distinct frontal asymmetry groups immediately prior to the TTE. This effect is illustrated in Figure 1.

**Figure 1**

*Frontal Alpha Asymmetry Experiment*



*Note.* Average value, *M±SE,* across the 2-min for each intervention block for each group, increase relative left, NFL, increase relative right, NFR, frontal cortical activity and passive control CON group.

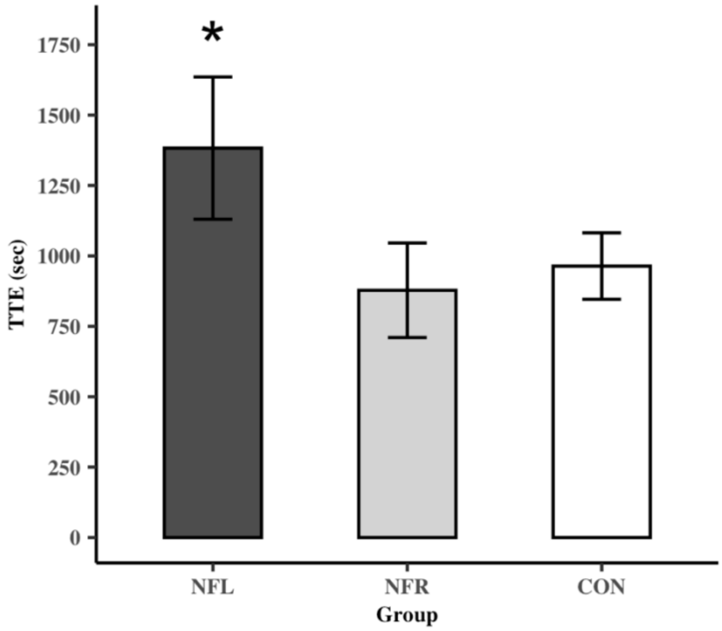
*Differences between groups NFL and NFR (**p <.05 and * p <.10).

### Cycling time to exhaustion test

Results of the TTE tests are summarized in Figure 2. We hypothesized that the NFL group would outperform the NFR and passive control groups. Orthogonal planned contrasts confirmed that the NFL group performed significantly better than the other two groups ($t(37)=2.03$, $p=.050$, $g_s=.64$), while the performance of the NFR and the passive control groups did not differ from each other, $t(37)=0.33$, $p=.744$, $g_s=.10$.

**Figure 2**

*Effect of EEG-Neurofeedback on Time-to-Exhaustion, Experiment 1A*



*Note*. *M±SE* for each group, increase relative left, NFL, increase relative right, NFR, frontal cortical activity and passive control CON group.

* Significant difference between NFL and controls group, NFR and CON ($p=.05$).

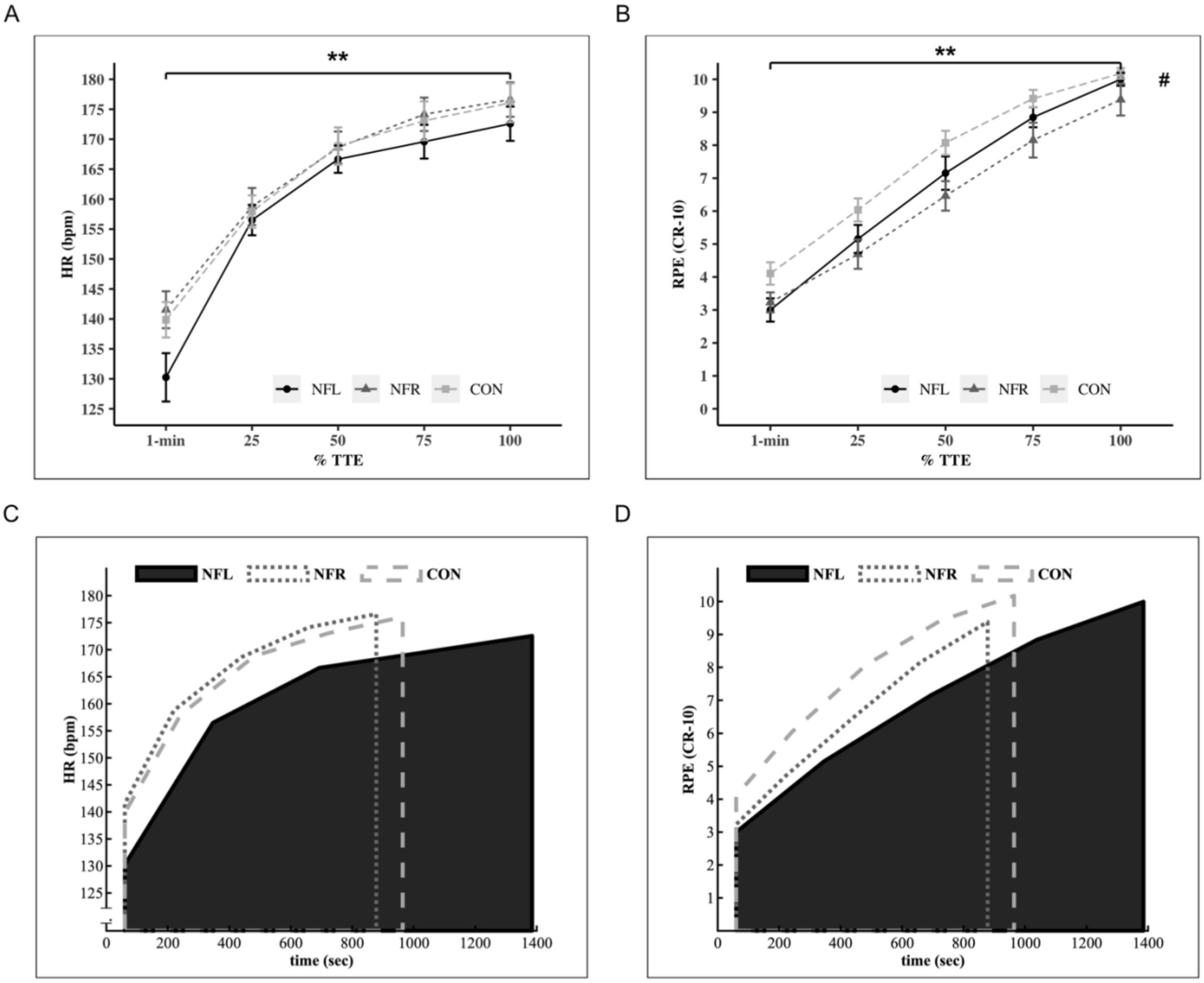
## RPE and HR

The 3 (Group) × 5 (Time) ANOVAs performed on the RPE and HR values revealed a main effect of time on RPE ($F(3,101)=400.25$, $p<.001$, $\eta_p^2=.91$), and HR ($F(2, 63)=270.55$, $p<.001$, $\eta_p^2=.88$). As expected, both variables increased significantly at every time point. There was also a significant effect of group for RPE ($F(2, 37)=3.54$, $p=.039$, $\eta_p^2=.16$). Post hoc tests indicated that RPE in the NFL group (6.8) did not differ significantly from that in the other groups, $p=.719$; however, RPE in the CON group (7.6) was significantly higher than RPE in the NFR group (6.4), $p=.012$. The HR data yielded no significant differences between groups ($F(2,36)=0.91$, $p=.412$, $\eta_p^2=.05$). No significant Group × Time interactions emerged. Effects are summarized in Figure 3A and 3B.

Overall, the AUC for RPE and HR were greater in the NFL compared to the other two groups, but contrast tests did not reach the statistical level for significance (RPE: $t(37)=1.84$, $p= .074$; and HR: $t(36)=1.74$, $p=.090$). This reflects the greater amount of total work performed by participants in NFL and implies a slower rate of increase in RPE and HR in the NFL group (see Figure 3C and 3D).

**Figure 3**

*Heart Rate (A) and Rating of Perceived Effort (B) during TTE and Area Under the Curve of HR (C) and RPE (D), Experiment 1A.*



*Note*. *M±SE,* HR and RPE at first minute and 25%, 50%, 75% and 100% of TTE test for each group.

**Significant main effect of time (*p*<.001); $^{\#}$ Significant difference between groups NFR and CON (*p*=.012).

## Control Analyses

Our control analyses are reported in full in the digital supplementary material (see Experiment 1A, Results, Supplementary Material). In brief, there were no baseline differences between the groups on any measures, indicating that our randomisation was effective (see Table 1). The 3 (Group) × 3 (Time) ANOVAs performed on the self-report measures of fatigue, vigour and state of self-control revealed no main effects for group and no Group × Time interactions. There were main effects for time, indicating that self-control and vigour decreased, and fatigue increased after the writing task and tended to increase again after the intervention. This confirmed that all our participants were in a similar state of fatigue and mild cognitive depletion prior to commencing the cycling TTE test. Finally, there were no group differences in the mean cadence or in any of the physiological assessments made at exhaustion, confirming that all groups reached a similar level of physiological fatigue at the end of the cycling TTE test (see Experiment 1A, Table S2, Supplementary Material).

**Table 1**

*Descriptive Statistic and One-Way ANOVA of the Demographic Characteristics and Baseline Variables*

| Measure | NFL | NFR | CON | *p* |
|---|---|---|---|---|
| | *M* (*SD)* | *M* (*SD)* | *M* (*SD)* | |
| n | 13 | 13 | 14 | |
| Age (yr) | 27 (6) | 27 (7) | 27 (8) | .977 |
| Weight (kg) | 74.0 (11.2) | 73.9 (18.4) | 70.5 (9.4) | .741 |
| Height (m) | 1.76 (0.06) | 1.73 (0.09) | 1.75 (0.10) | .793 |
| BMI (kg·m$^{-1}$) | 24 (4) | 24 (5) | 23 (2) | .623 |
| $\dot{V}O_2$ max (ml·kg·min$^{-1}$) | 46.8 (12.4) | 43.0 (11.6) | 45.7 (9.4) | .672 |
| PPO (W) | 278 (82) | 254 (70) | 285 (76) | .556 |
| Max HR (bpm) | 176 (6) | 174 (10)[a] | 175 (10) | .674 |
| Fatigue (BRUMS) | 2.5 (2.3) | 3.3 (3.1) | 3.7 (3.2) | .528 |
| Vigour (BRUMS) | 8.7 (1.9) | 7.8 (4.1) | 8.21 (2.8) | .752 |
| SSCCS | 142 (13) | 139 (20) | 135 (21) | .620 |
| Alpha Asymmetry (a.u.) | 0.02 (0.09) | 0.00 (0.10) | - 0.01 (0.05) | .542 |

*Note*. BMI = Body Mass Index; $\dot{V}O_2$max = Maximal oxygen consumption; PPO = Peak Power Output; SSCCS = State of Self-Control Capacity Scale.

[a] n = 12 because of recording problems during the test.

## Conclusion and Introduction to Experiment 1B

The results from Experiment 1A showed that EEG-neurofeedback can be used to non-invasively modify frontal hemispheric asymmetry. More importantly, they suggested that greater relative left frontal cortical activity enhanced cycling-based endurance exercise performance. However, between-person variability in many psychophysiological signals can be high such that some researchers have argued that within-person designs are preferred (e.g., Jennings et al., 2007). As such, to examine the replicability and robustness of our finding, we followed up Experiment 1A with a fully repeated measures design in Experiment 1B.

## Experiment 1B: Within-Subject Design

## Methods

### Design, Participants, and Procedures

A cross-over, single-blind, counterbalanced design was used for the second experiment whereby the same individuals who had received the EEG-neurofeedback interventions in Experiment 1A (groups NFL and NFR) were tested for a third experimental session. The twenty-six NFL and NFR participants (*n* = 17 males and *n* = 9 females) from Experiment 1 performed the additional, third experimental visit. This was identical to the second experimental session described in Experiment 1A (see visit 2 above for details), except that participants received the opposite neurofeedback intervention in this additional session. Accordingly, in Experiment 1B, all 26 participants received both the NFL and NFR interventions on separate occasions, allowing for within-subject comparisons. The order of the two visits was counterbalanced across participants, who were scheduled at the same time of day to control for possible circadian rhythm effects on physical performance and alpha asymmetry. Participants were allowed a minimum of 3 days and a maximum of 3 weeks from the previous experimental session to perform the additional visit. Participants were asked to keep their training routine consistent throughout their involvement in the study. All apparatus, measures and other procedures were identical to those reported in Experiment 1A.

### Data Reduction

**HR and RPE**. The HR and RPE values attained in each TTE test at the minutes corresponding to the 25%, 50%, 75% and 100% of the total endurance time were used for the within-subject comparison ("relative iso-time" in Nicolò et al., 2019). For the first time point, we used the values recorded at the end of the first minute of each test. In addition, AUCs were derived from RPE and HR data recorded during the TTE with the same formula described in Experiment 1A (see data reduction above).

### Statistical Analysis

**Main Analyses**. We performed 2 (Condition) × 6 (Block) repeated measures ANOVA to assess the effectiveness of our neurofeedback intervention in manipulating frontal asymmetry. We performed a paired-samples *t*-test to compare the TTE achieved by participants during the NFL and NFR conditions. Finally, we performed 2 (Condition) × 5 (Time) ANOVAs to examine the effects of neurofeedback on RPE and HR throughout each cycling TTE test and paired sample *t*-test to test the effect of neurofeedback on AUC for RPE and HR.

**Control Analyses.** Paired samples *t*-tests were used to compare baseline vigour and fatigue, self-control, and alpha-asymmetry across the two experimental visits. Paired samples *t*-tests also compared mean cadence, and HR, RPE and blood lactate level at exhaustion. We employed separate 2 (Condition) × 3 (Time; baseline, post written task, post neurofeedback) repeated measures ANOVAs to examine the effect of the writing task and the neurofeedback interventions on reported self-control, fatigue, and vigour. Significant interaction effects were investigated with orthogonal contrasts. For all analyses, statistical significance was set at $p \leq 0.05$ and effect sizes were estimated with Cohen's $d_{av}$ calculated with the average standard deviation and corrected as Hedges's $g_{av}$ (see Formula 10, Lakens, 2013).

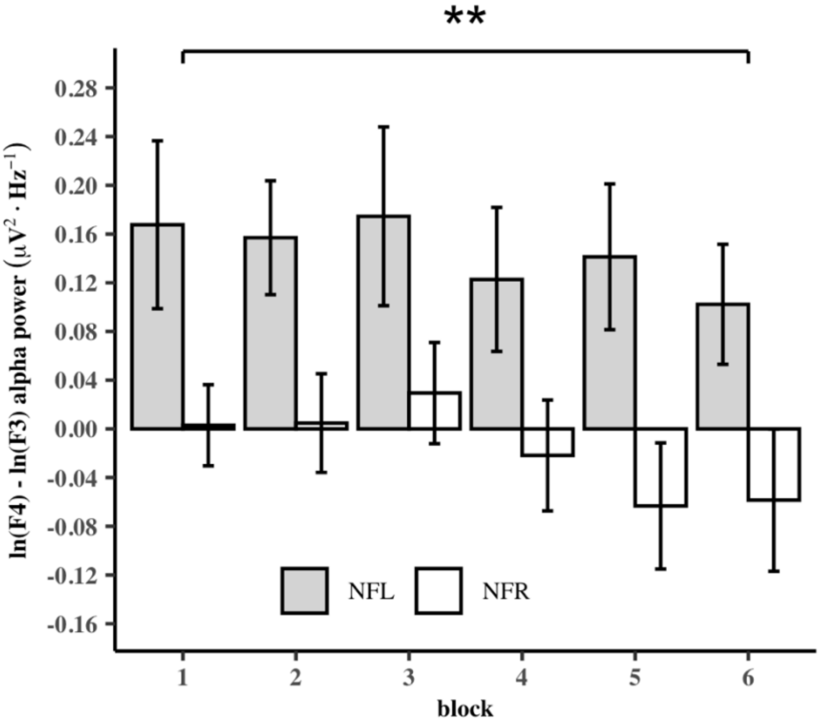
# Results

## Alpha asymmetry

A 2 (Condition) × 6 (Block) ANOVA performed on the alpha asymmetry indices revealed a significant main effect of condition ($F(1,25)=4.81$, $p=.038$, $\eta_p^2=.16$). Alpha asymmetry was significantly greater (and positive; $0.14 \pm 0.28$ $\mu V \cdot Hz^{-1}$) indicating dominant left-sided frontal cortical activity in the NFL condition, compared to the NFR condition ($-0.02 \pm 0.16$ $\mu V \cdot Hz^{-1}$), where the smaller (and negative) score indicates dominant right-sided frontal activity. This finding confirms that our neurofeedback intervention was effective in establishing two distinct asymmetry conditions, and the effect emerged across all blocks (Figure 4). There was no Block main effect or Block × Condition interaction.

**Figure 4**

*Frontal Alpha Asymmetry, Experiment 1B*



*Note. M±SE*, alpha asymmetry across the 2-min for each neurofeedback block for each condition, increase relative left, NFL, increase relative right, NFR, frontal cortical activity. *Significant main effect of condition ($p=.038$).

## Time to Exhaustion

The TTE test was longer in the NFL condition (1167 ± 831 s) compared to the NFR condition (1049 ± 638 s). This difference, 118 s, 95% CI [14, 221] was significant supporting our finding in Experiment 1A ($t(25)=2.34$, $p=.028$, $g_{av}=.16$).

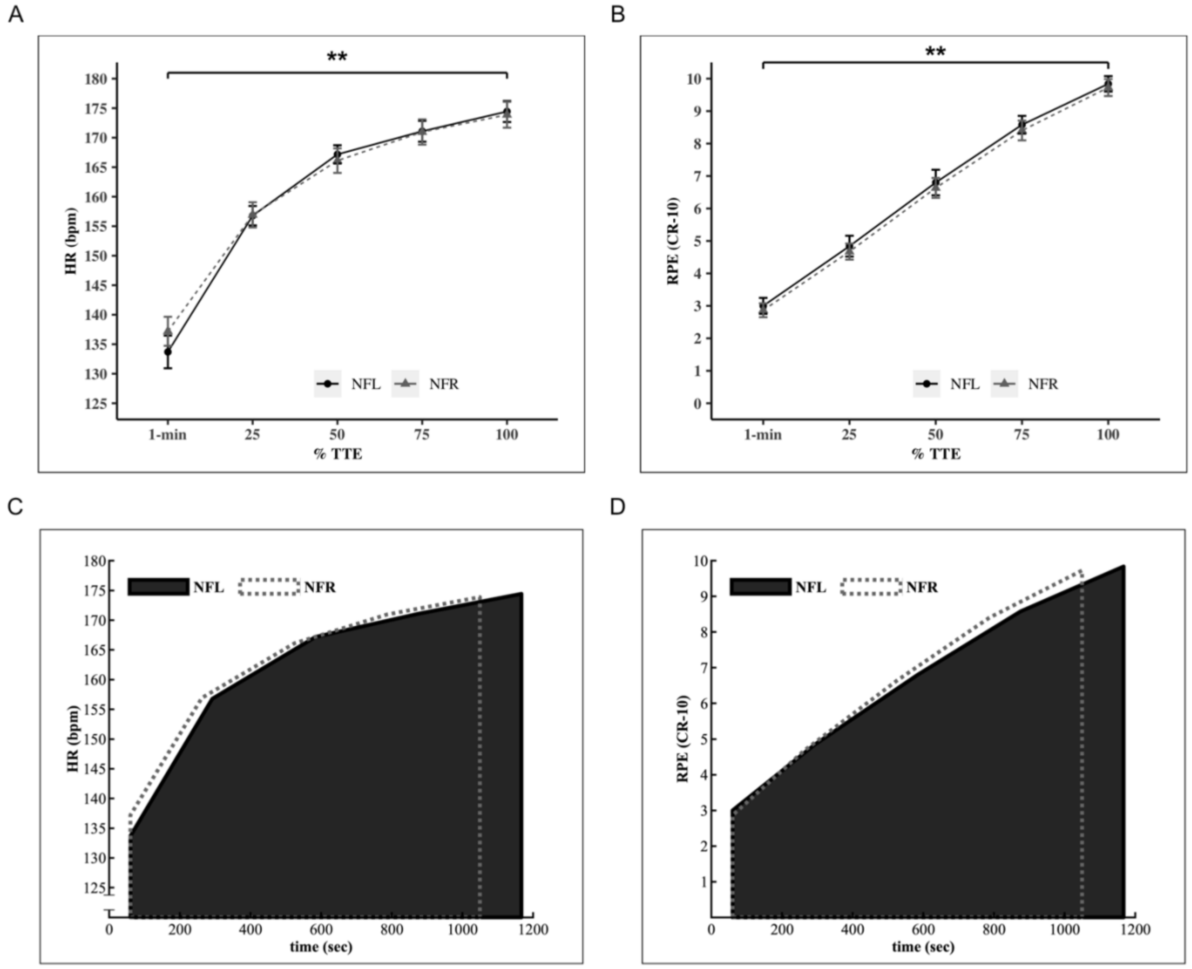
## RPE and HR

The 2 (Condition) × 5 (Time) ANOVAs performed on the RPE and HR values revealed a significant main effect of time ($F(2,60)=312.26$, $p<.001$, $\eta_p^2=.93$; $F(2,35)=178.21$, $p<.001$, $\eta_p^2=.89$, respectively). Both RPE and HR increased significantly at every time point ($p$-values of the repeated contrasts between time points were <.001). There were no significant effects of condition, or Condition × Time interactions for either RPE, or HR. These results are summarised in Figure 5A and 5B.

Areas under the curves were greater in the NFL condition compared to the NFR condition for both HR ($t(22)=2.51$, $p=.020$, $g_{av}=.17$), and RPE ($t(24)=2.52$, $p=.019$, $g_{av}=.12$) (Figure 5C and 5D). Given the aforementioned empirical findings (i.e., lack of quartile differences and significant TTE effect) and the visual representation in Figures 5C and 5D, it would appear that when participants were under the NFL condition, they persisted on the cycling task for longer demonstrating a suppressed rate of increase in RPE and HR.

**Figure 5**

*Heart Rate (A) and Rating of Perceived Effort (B) during TTE and Area Under the Curve of HR (C) and RPE (D) during TTE, Experiment 1B*



*Note*. *M±SE*, HR and RPE at first minute and 25%, 50%, 75% and 100% of the TTE test for each condition.

**Significant main effect of time (*p*<.001).

### Control Analyses

Our control analyses are reported in full in the supplementary material (Supplementary Material Experiment 1B, Results); they confirmed our expectations. In brief, there were no baseline differences across the conditions, indicating that participants reported to the laboratory in a similar state for both of their experimental visits. The 2 (Condition) × 3 (Time) ANOVA performed on the self-report measures of fatigue, vigour and state of self-control capacity revealed no main effects for Condition and no Condition × Time interaction. There were main effects for Time, indicating that self-control and vigour decreased, and fatigue tended to increase after the writing task and the neurofeedback intervention. This confirmed that our participants were in a similar state of mild cognitive depletion prior to the cycling TTE in both conditions. Finally, there were no differences in the mean cadence of the TTE tests or in any of the physiological assessments made at exhaustion, confirming that participants displayed a similar level of physiological fatigue in both conditions (see Supplementary Material Experiment 1B, Table S3).

## Discussion

### Main Findings

This is the first investigation to assess the effect of neurofeedback on whole-body endurance exercise performance. The results from both datasets provide consistent evidence that increasing relative left frontal cortical activity (NFL) via EEG-neurofeedback has a beneficial effect on endurance exercise performance. In Experiment 1A, participants who received this NFL intervention were able to cycle for approximately six minutes (about 30%) longer than participants who received either an increase in relative right frontal cortical activity (NFR) via neurofeedback, or the passive control group (CON) who received no neurofeedback intervention. This finding was replicated in Experiment 1B using a within-subject design when the same individuals performed the TTE test after receiving both NFL and NFR on separate occasions. In this instance, participants cycled for approximately two minutes (11%) longer in the NFL condition compared to the NFR condition.

Importantly, in Experiment 1A, TTE performance was not significantly different between the NFR and CON groups. Therefore, we can exclude the possibility that the NFL performance improved simply because individuals underwent a neurofeedback intervention per se (e.g., placebo effect), or due to mechanisms underlying the neurofeedback training (e.g., operant conditioning). Also, the physical stimuli during the interventions were the same across conditions, adding further evidence to indicate that the significant effect of NFL on performance was due to changes in frontal asymmetry (i.e., were genuine) rather than any other features associated with the experimental protocol (e.g., auditory and visual stimuli).

A more invasive brain stimulation method, transcranial direct current stimulation (tDCS) has been reported to elicit either a 23% improvement (Angius et al., 2018), or no improvement (Angius et al., 2015) of endurance performance when assessed using a within-subject design. However, ethical concerns that have been raised about tCDS may limit its mass uptake in applied settings (e.g., Davis, 2013). Our findings are the first to confirm that a non-invasive approach to modifying brain activity via EEG-neurofeedback could offer a practical and realistic performance enhancing alternative for individuals or situations where tCDS is not acceptable, or viable.

## Mechanisms

In the current study, as expected, HR and perceived effort during the TTE test increased over time and reached on average 96% and the 100% of their maximal values, respectively. Contrary to our hypothesis, NFL did not significantly reduce perception of effort during any TTE. Specifically, ANOVAs failed to reveal the expected Group x Time (Experiment 1A) or Condition x Time (Experiment 1B) interactions for RPE. While previous studies show that psychological interventions can improve endurance exercise performance by reducing perception of effort during the task (Blanchfield et al., 2014), the results of our study suggest that EEG-neurofeedback may act in a different way. Rather than reducing perception of effort, NFL may instead have supported participants to exercise for longer while experiencing a high level of effort. Hence, NFL allowed participants to perform a greater amount of physical work when fulfilling their goal to exercise for as long as possible. To provide some support for this interpretation, we found differences in AUC of RPE and HR which were marginally greater for NFL compared to NFR and CON in Experiment 1A and significantly greater after NFL compared to NFR in Experiment 1B. Since the absolute levels of RPE and HR at the end of each quartile of exercise were the same between groups and conditions (i.e., no ANOVA interactions), the greater AUC for NFL can be attributed to differences in the length (i.e., time; longer in NFL) rather than the height (i.e., RPE and HR) factors in the AUC formula. Figures 3 and 5 illustrate this effect and reveal a slower rate of increase in RPE and HR for NFL, reflecting the longer time taken to reach the same terminal levels as achieved after NFR or CON, implying greater sustained effort in NFL than in NFR or CON. Although we reported discrepant findings between our AUC and the traditional ANOVA approach to analysing time-series data in endurance studies, these were highly informative. We encourage researchers to further explore the merits of the AUC approach in future endurance-oriented experiments.

At a cortical level, our results imply that NFL prompted a neurophysiological shift towards approach motivation and increased behavioural persistence. This perspective is supported by the fact that our NFL neurofeedback intervention led to significantly greater left-sided frontal cortical activity. Pertinently, relative left frontal cortical activity is involved in approach motivation, which is considered to represent the tendency to move toward something (Harmon-Jones & Gable, 2018). Approach-related processes engage the same neural activation underlying local attentional scope. Specifically, relative left frontal-central asymmetry induced by approach-related stimuli predicted narrowed attentional scope (Harmon-Jones & Gable, 2009) which could assist goal-directed action by narrowing the attention toward task-relevant information (Gable & Harmon-Jones, 2010) and increasing cognitive stability and persistence (Liu & Wang, 2014). For example, in the context of the current endurance exercise, left-sided frontal activity may help individuals maintain focus and engagement with their progressively more painful and fatiguing task, thereby delaying the urge to withdraw and stop. Consistent with this interpretation, Schiff et al. (1998) used a lateral muscular hand contraction to modify asymmetric frontal cortical activity and found higher persistence on an unsolvable puzzle after the right lateral muscular contractions (said to increase left cortical activity) compared to the contralateral contraction and passive control. Taken together these findings suggest that greater relative left frontal cortical activity, following NFL, facilitated cognitive control by delaying attentional disengagement. This, in turn, would allow individuals to allocate attention towards coping with the increasing time-on-task demand of exercise helping them to tolerate high effort for longer. Further support for this may be gleaned from the fact that activation of the left dorsolateral prefrontal cortex (DLPFC) has been found when individuals implemented cognitive control to form and maintain task-goal representation of the Stroop test (MacDonald et al., 2000). Similarly, Berkman and Lieberman (2010) used fMRI while participants performed a virtual task to examine the relationship between asymmetric brain activation, stimulus valence, and motivational direction. They found that relative left frontal activation of the DLPFC was associated with action (eat), independently from the stimulus valence (pleasant food or disgusting food). Because relative left frontal activity increased in response to approach-related actions coupled with both positive stimuli and negative stimuli, the authors argued that left-sided activity in the DLPFC should be involved in self-regulatory processes relevant for successful goal pursuit.

In addition to being interpretable via models of approach and avoidance motivation, our effects are also broadly in accordance the valence model (Heller, 1993) and the capability model (Coan et al., 2006) of frontal hemispheric asymmetry. The valence model argues that increased left-sided frontal asymmetry elicits more positively valanced emotions, and previous research has demonstrated that greater positive emotions can facilitate endurance performance (e.g., Hutchinson et al., 2018). However, the valance hypothesis has been challenged by research demonstrating that while left-frontal activation is associated with some positive emotions, it is also associated with the negative emotion of anger (Harmon-Jones, 2003; Harmon-Jones & Allen, 1998; Hortensius et al., 2012). Accordingly, frontal asymmetry may not be associated with valence per se, rather it reflects the motivational system engaged by that stimulus or situation (Davidson & Irwin, 1999). This is why we preferred the approach and avoidance motivational account of frontal asymmetry to the valence model.

The capability model proposes frontal hemispheric asymmetry as a predictor of individual capability for displaying certain affective styles (Coan et al., 2006). More specifically, it predicts that individuals displaying greater left over right frontal activation will also have more positive affective responses to external situations or stimuli, whereas individuals reporting greater right over left frontal activation, within the same context, will experience more negative affective responses (see Coan et al., 2001). As positive affect can enhance endurance (Hutchinson et al., 2018), our results could be interpreted as supportive of the capability model. Future research could incorporate features to tease apart the capability model and the approach and avoidance model to shed more light on which of these explanations provides the mechanism that underlies the effects of hemispheric asymmetry neurofeedback on performance.

### Limitations and Future Directions

Despite the encouraging findings provided, some limitations should be considered when interpreting the results. Firstly, from a theoretical perspective, cortical activity was measured during the neurofeedback procedure, but not afterwards, nor during the physical task. Therefore, despite confirming the validity of a single session of EEG-neurofeedback (Peeters et al., 2014), we can only assume that the neural changes induced during the single session of neurofeedback persisted throughout the exercise. Further research is warranted to assess the longevity of neurofeedback training effects and provide additional support for the relationship between frontal asymmetric cortical activity and performance.

Secondly, our theory-driven approach was focused on perception of effort. However, it may be possible that other psychological variables mediated the effect of the frontal asymmetric cortical activity during the exhaustive cycling task. In this regard, Allen et al. (2001) demonstrated that neurofeedback to modify asymmetric frontal cortical activity altered self-reported emotional responses elicited by external stimuli. It is well-known that feelings can change throughout the exercise (Hardy & Rejeski, 1989) and influence performance (e.g., Hutchinson et al., 2018); therefore, future studies should assess affective responses during endurance exercise following this neurofeedback intervention. Similarly, additional markers of approach motivation could be assessed to further investigate the psychological mechanisms underlying the relationship between asymmetric frontal cortical activity and behaviour (see Harmon-Jones & Gable, 2018).

It should be noted that due to the intended design of our experiment, our effects emerged when participants entered exercise in a state of mild cognitive depletion and fatigue, as indicated by the reduction in self-reported self-control that remained lower than baseline after the manipulation. Thus, our performance results suggest that the left-sided frontal cortical asymmetry may be particularly relevant when effort is aggravated by prior fatigue. However, it would be useful for future research to replicate our experiments without prior fatigue and/or with varying levels of prior fatigue to test the generalizability of our findings. One could argue that any benefits of neurofeedback on physical endurance could be stronger without any prior cognitive fatigue since this could help participants achieve more intense left frontal activation during the neurofeedback intervention, beyond the levels achieved here. These predictions await future testing.

Lastly, the sample of the present study comprises recreational athletes, as such, it is not clear if the effect found will generalize to elite athletes. On the one hand, elite athletes are already closer to their endurance limits than recreational performers, possibly creating a ceiling with less scope for neurofeedback (or any) intervention benefits to manifest. On the other, the reduced between- and within-person variability displayed by elite compared to recreational performers may render greater scope for statistically meaningful "marginal gains" to emerge in elite performers. This can be tested by future research.

### Practical Applications

From an applied perspective, our data support the use of EEG-neurofeedback in the context of endurance performance and indicate that the application of EEG-neurofeedback for as little as 12 minutes could offer a safe and ethically viable approach to performance enhancement for athletes who engage in endurance exercise events lasting for around 20 minutes. In addition, Ring et al. (2015) reported that athletes undergoing repeated sessions of neurofeedback training could learn to regulate their own cortical activity even when they are not receiving the physical feedback. This offers a valuable advantage in an applied setting where athletes might eventually be able to reproduce the performance-boosting brain activity without any equipment, following a short period of neurofeedback training.

## Conclusion

This is the first investigation to show that neurofeedback can be used as a form of non-invasive brain stimulation to improve endurance performance. Specifically, increasing relative left frontal cortical activity via neurofeedback was able to improve exhaustive exercise performance by 30% and 11% using between-group and within-subject designs, respectively. Despite this performance enhancement, neurofeedback did not lead to differences in perception of effort during the TTE tests. Thus, from a theoretical perspective, neurofeedback might act in a different way to other cognitive interventions (e.g., Blanchfield et al., 2014) that acutely enhance endurance capacity. Our novel application of AUC analyses generated findings indicative that neurofeedback might aid endurance performance through increased goal-directed persistence resulting from a shift towards greater approach motivation. As such, the current study and associated datasets introduce an original *and* effective brain-oriented endurance performance intervention, reveal a new potential mechanism bridging left-sided frontal cortical asymmetry and whole-body endurance exercise performance, and can be used as an exemplar by future theory-driven neurofeedback investigations interested in enhancing endurance performance.

# Supplementary Material

The complete results of the control analyses are presented as supplementary material.

## Supplementary Material Experiment 1A

### *Results Control Analyses*

**State of Self-Control Capacity Scale (SSCCS)**. On average, the written task lasted 1289 ± 324 s with no significant differences between the three groups ($F(2,37)=0.35$, $p=.706$). The 3 (Group) × 3 (Time) ANOVA on self-reported state of self-control state revealed a significant main effect of time ($F(2,52)=7.80$, $p=.002$, $\eta_p^2=.19$). Repeated contrasts showed that the writing task significantly reduced state of self-control capacity compared to baseline ($F(1,33)=6.48$, $p=.016$, $\eta_p^2=.16$). There were no significant effects of group ($F(2,33)=0.13$, $p=.877$, $\eta_p^2=.01$) and no Group × Time interaction ($F(3,52)=0.87$, $p=.469$, $\eta_p^2=.05$).

**Vigour and Fatigue.** The 3 (Group) × 3 (Time) ANOVAs performed on the vigour and fatigue subscales reported no significant differences between the three groups (fatigue: $F(2,36)=0.06$, $p=.940$; vigour: $F(2,36)=0.02$, $p=.984$) and no significant Group × Time interactions (fatigue: $F(3,51)=0.24$, $p=.858$; vigour: $F(4,72)=0.87$, $p=.484$). However, there was a significant main effect of time on both fatigue ($F(1,51)=5.43$, $p=.014$, $\eta_p^2=.13$) and vigour ($F(2,72)=9.44$, $p<.001$, $\eta_p^2=.21$). Repeated contrasts showed that fatigue tended to increase throughout the visit compared to baseline with a significant increment after the interventions (post written tasks: $F(1, 36)=2.89$, $p=.098$, $\eta_p^2=.07$; post neurofeedback: $F(1,36)=5.63$, $p=.023$, $\eta_p^2=.14$). Vigour decreased over time and was significantly lower after the interventions (post written tasks: $F(1,36)=3.25$, $p=.080$, $\eta_p^2=.08$; post neurofeedback: $F(1,36)=7.82$, $p=.008$, $\eta_p^2=.18$).

**Table S2**

*Descriptive Statistic and One-Way ANOVAs of Mean Cadence of TTE Tests and Physiological and Perceptual Variables at Exhaustion (Experiment 1A).*

| Measures | NFL | NFR | CON | *F(df)* | *p* | $\eta_p^2$ |
|---|---|---|---|---|---|---|
| | *M (SD)* | *M (SD)* | *M (SD)* | | | |
| Mean cadence (rpm) | 74 (7) | 71 (9) | 77 (9) | 1.47(2,37) | .244 | .07 |
| Blood lactate (mmol·$L^{-1}$) [a] | 7.8 (1.6) | 8.3 (2.2) | 6.1 (3.1) | 2.2(2,23) [b] | .129 | .17 |
| RPE | 10.0 (0.7) | 9.4 (1.7) | 10.2 (0.6) | 1.80(2,37) | .179 | .09 |
| Heart Rate (bpm) [a] | 173 (10) | 177 (10) | 176 (12) | 0.49(2,36) | .616 | .02 |

*Note*. NFL = neurofeedback to increase relative left cortical activity group; NFR = neurofeedback to increase relative right cortical activity group; CON, passive control group.

[a] *N* = 39 because of technical problems with the equipment during the recording

[b] Welch' s F

## Supplementary Material Experiment 1B

### *Results Control Analyses*

**Baseline Measures.** Paired sample *t*-tests revealed no differences between the two conditions in the baseline measures of fatigue, $t(25)=-0.97$, $p=.339$; vigour, $t(25)=1.38$, $p=.181$; SSCCS, $t(25)=-0.20$, $p=.840$; alpha asymmetry, $t(25)=0.18$, $p=.861$.

**State of Self-Control Capacity Scale (SSCCS).** The 2 (Condition) × 3 (Time) ANOVA revealed a significant main effect of time on state of self-control capacity ($F(1,25)=5.41$, $p=.023$, $\eta_p^2=.20$); repeated contrasts confirmed that capacity decreased significantly after the written task ($F(1,21)=6.01$, $p=.023$, $\eta_p^2=.22$). There was no significant main effect of condition and no significant Condition × Time interaction ($F(1,21)=0.31$, $p=.584$, $\eta_p^2=.02$); $F(2,39)=0.93$, $p=.398$, $\eta_p^2=.04$, respectively).

**Vigour and Fatigue.** The 2 (Condition) × 3 (Time) ANOVAs performed on fatigue and vigour revealed a significant main effect of time ($F(1,30)=6.23$, $p=.013$, $\eta_p^2=.21$; $F(1,36)=5.28$, $p=.016$, $\eta_p^2=.18$, respectively). Repeated contrasts showed that fatigue increased significantly after the neurofeedback interventions ($F(1,24)=7.11$, $p=.014$, $\eta_p^2=.23$) and vigour decreased significantly after written task ($F(1,24) = 4.76$, $p=.039$, $\eta_p^2=.17$). Main effects of condition and the interactions Condition × Time were not significant for either scales.

**Table S3**

*Descriptive Statistic and t-tests of Mean Cadence of the TTE Test and Physiological and Perceptual Variables at Exhaustion (Experiment 1B).*

| Measures | NFL | NFR | *t(df)* | *p* | $g_{av}$ |
|---|---|---|---|---|---|
| | *M (SD)* | *M (SD)* | | | |
| Mean cadence (rpm) [a] | 73 (10) | 72 (8) | 1.01 (24) | .321 | .074 |
| Blood lactate (mmol·$L^{-1}$) [a] | 8.0 (1.9) | 8.5 (2.5) | -1.25 (24) | .225 | .224 |
| RPE | 9.5 (1.3) | 9.7 (1.9) | -0.63 (25) | .535 | .143 |
| Heart Rate (bpm) [a] | 174 (9) | 174 (11) | 0.49 (22) | .626 | .069 |

*Note*. NFL = neurofeedback to increase relative-left cortical activity; NFR = neurofeedback to increase relative right cortical activity. No significant differences in physiological responses during and at the end of the TTE.

[a] *N* = 25 and 23 because of technical problems with the equipment during the recording.

# CHAPTER 5

# EEG-NEUROFEEDBACK, MENTAL FATIGUE AND ENDURANCE PERFORMANCE

# Abstract

**Objective:** Preliminary results have demonstrated that the EEG-neurofeedback to increase left-sided frontal cortical asymmetry after the performance of a cognitively demanding task improved cycling time-to-exhaustion test performance. The present study investigated the mechanisms underlying this effect by examining the psychological and physiological variables that are associated with left-sided frontal cortical asymmetry and could enhance endurance performance. **Method:** The study consisted of a randomised, counterbalanced within-subject design with two experimental conditions. In one condition participants received the neurofeedback to increase relative left frontal cortical activity (NFL) after they had performed a mentally fatiguing task. On a separate experimental visit, participants received the increase relative right cortical activity neurofeedback (NFR) following the same cognitive task. After the interventions, participants performed a time-to-exhaustion (TTE) test on a cycle ergometer. Self-reported and electroencephalographic measures of mental fatigue were recorded prior to and after the cognitive task, moreover attentional focus and affective state during the TTE test were recorded. **Results:** Self-reported mental fatigue and frontal theta-band power increased significantly after the cognitive task in both conditions. This time the EEG-neurofeedback had a smaller yet significant effect on frontal alpha asymmetry. The NFL neurofeedback did not improve significantly cycling performance and there were no differences between conditions in affective responses and attentional strategies assessed during the TTE test. **Conclusion:** The neurofeedback intervention elicited greater relative left frontal cortical activity, however this time the effect was smaller compared to previously reported effects. No significant effects on behavioural, affective and physiological variables were found following the neurofeedback interventions.

## Introduction

Electroencephalogram (EEG)-neurofeedback is a non-invasive technique to modify cortical brain activity. This technique has been applied in clinical (Hammond, 2007) and performance (Gruzelier, 2014; Mirifar et al., 2017) contexts to reproduce brain patterns associated with specific cognitive state and/ or superior performance. Very recently Mottola et al. (2021) were the first to demonstrate that the EEG-neurofeedback could provide a beneficial effect to endurance performance. Mottola et al. (2021) adopted a single session of neurofeedback to temporarily modify frontal cortical asymmetry and reported that neurofeedback to increase relative left frontal cortical activity improved the performance of a cycling time-to-exhaustion test. This result is a step forward for research on neurofeedback and endurance performance. Nonetheless, some of the mechanisms behind this performance enhancement remain unknown. The present experiment aims to shed light on the psychophysiological mechanisms underpinning the relationship between the neural activity elicited with the EEG-neurofeedback and endurance performance.

The neurofeedback intervention used by Mottola et al. (2021) was built on the motivational model of asymmetric frontal cortical activity (Davidson, 1992) and the psychobiological model of endurance performance (Marcora, 2008). The first assumes that asymmetric frontal cortical activity reflects the lateralization of approach and withdrawal processes over the left and right frontal cortex, respectively (Davidson, 1992; Harmon-Jones & Gable, 2018). The latter explains endurance performance based on the motivation intensity theory (Wright, 2008). According to the psychobiological model of endurance performance, the limits of endurance exercise is a voluntarily task-disengagement that occurs when the effort required by the exercise exceeds the maximal effort the individual is willing to exert in order to succeed in the task or the effort seemed beyond his/her ability (Marcora, 2008; Marcora & Staiano, 2010). This psychobiological model hence predicts that any intervention that reduces the perception of effort or increases potential motivation should improve endurance performance (see for example Blanchfield et al., 2014). Although in Mottola et al. (2021) the EEG-neurofeedback to increase relative left frontal cortical activity improved the performance, it did not influence ratings of perceived effort or heart rate measured during the cycling time-to-exhaustion. Rather individuals were able to persist on the time-to-exhaustion test for longer while experiencing an increasing level of effort. Hence, the authors suggested that the intervention to increase relative left frontal cortical activity allowed participants to sustain a greater amount of physical work to fulfil their goal of exercise for as long as possible. Accordingly, Schiff et al. (1998) externally manipulated asymmetric cortical activation via unilateral muscular contraction and demonstrated that relative left over right frontal cortical activity was associated with increased persistence during a cognitive task. Furthermore, Berkman & Lieberman (2010) reported that left-sided activation in the dorsolateral prefrontal cortex measured with fMRI was associated with approach motivation for action independently from the valence of the stimulus driving the action. These studies suggest that approach-orientated relative left frontal cortical activation could support key cognitive and affective processes for the regulation of goal-directed behaviour and, in particular, of endurance performance. With this in mind, the present study investigated key psychophysiological variables for endurance performance that have been associated with asymmetric frontal cortical activity.

From a cognitive perspective, research has shown that approach-motivated state drives action preparation (Gable et al., 2016), narrowed cognitive scope (Gable & Harmon-Jones, 2008; Domachowska et al., 2016) and cognitive stability (Liu & Wang, 2014) which, in turn, facilitates action toward goal and perseverance, supporting goal pursuit in general (Gable & Harmon-Jones, 2010). Consistently with that, Harmon-Jones and Gable (2009) investigated whether the neural activation for approach motivation (left-sided frontal cortical activity) was associated with the effect of approach motivation on narrowed attention. In their study, left-sided cortical activation was found in response to appetitive stimuli (e.g., dessert pictures) and predicted the performance (reaction time) of local-target trial which is a measure of narrow (vs broad) attentional scope.

In addition to cognitive scope, asymmetric frontal cortical activity is related to approach/withdrawal affective responses (e.g., Allen et al., 2001, Peterson et al., 2011). Allen et al. (2001) showed that the manipulation of asymmetric frontal cortical activity via EEG-neurofeedback influenced affective responses to emotional-evocative stimuli and manipulated left-sided frontal cortical asymmetry, in particular, resulted in more positive affective responses.

Prolonged exercise is characterized by increasing level of effort and displeasure (e.g. Kilpatrick et al., 2007; Hartman et al., 2019). Hence, athletes performing endurance exercise engage specific attentional focus and cognitive strategies to override the urge to quit arising from these aversive sensations and reach their training and/or competition goal (McCormick et al., 2019; Taylor et al., 2018; Whitehaed et al., 2018). Importantly, several investigations showed that fatiguing cognitive activities had a detrimental effect on the following exercise performance by exacerbating the perception of effort (Marcora et al., 2009; Van Cutsem et al., 2017 for a review). As a result, mentally fatigued individuals may experience greater signals to stop (Martin et al., 2018; Schiphof-Godart et al., 2018). Therefore, cognitive strategies and goal-orientated attention during the exercise could become even more relevant after the performance of cognitively demanding activities. In accordance with this, the performance of mentally fatiguing tasks has been associated with reduced cognitive control, less efficient local processing and task disengagement (e.g., Hopstaken et al., 2016; van der Linden & Eling, 2006). Left-sided frontal cortical activity may elicit positive and approach-orientated processes that promote goal-exercise achievement, e.g., persistence in a cycling time to exhaustion, especially when the performance goal is dampened by mental fatigue. Particularly, relative left frontal cortical asymmetry could prompt goal-orientated thoughts and tune the attention toward performance-related cues (e.g., cadence, technique) and adaptive cognitive strategies (e.g., chunking) while inhibiting thoughts that disadvantage performance e.g., pain, discomfort, and distraction (Brick et al., 2014; Whitehead et., 2018). At the same time, relative left frontal cortical activation could be associated with more positive affect during the exercise and, in turn, attenuate the increasing feeling of displeasure that arises at high exercise intensity (Kilpatrick et al., 2007) and, especially, close to physical exhaustion (e.g., Hartman et al., 2019). That is, the neurofeedback intervention to increase relative left cortical activity could elicit more positive affective responses to demanding exercise hence allowing to sustain a greater amount of work. In line with this assumption, previous research showed that the decline in positive affect during a cycling time-to-exhaustion test was negatively correlated with performance (Hartman et al. 2019). That is, the steeper was the decline in positive affect the shorter was the cycling time-to-exhaustion. On the contrary positive affective responses to music manipulation allowed individuals to sustain greater work (Elliot et al., 2005).

## The Present Study

The present study aimed at replicating the results found by Mottola et al. (2021) and examining more in-depth the effect of the neurophysiological shift induced with EEG-neurofeedback on psychological and physiological responses to endurance exercise in a mentally fatigued state. A multidisciplinary assessment of mental fatigue was implemented before and after the cognitive task which preceded the EEG-neurofeedback intervention and the cycling time-to-exhaustion test. Specifically, subjective feeling of mental fatigue and cognitive “depletion” and power of theta frequency band were measured to evaluate mental fatigue and predicted to increase after the cognitive task (see Van Cutsem et al. 2017; Washer et al, 2014). The effect of EEG-neurofeedback interventions to modify frontal hemispheric activity was assessed on affective responses and attentional focus during the cycling time-to-exhaustion test. Particularly, we adopted a semi-structured interview which assessed three categories of attentional focus as well as specific thoughts underlying those categories and examined whether (and how) relative frontal cortical asymmetry would direct attentional focus toward advantageous and performance-orientated thoughts (Brick et al., 2014; Whitehead et., 2018). Furthermore, we measured the affective responses during the exercise and predicted that neurofeedback to increased relative-left frontal cortical activity would lead to more positive affect. In addition, we recorded electromyography, EMG, during the TTE to test the effect of neurofeedback on muscular efficiency as well as heart rate variability during the neurofeedback interventions.

## Methods

### Participants

A priori power analysis (GPower) based on our previous study (Mottola et al., 2021) reporting a significant and medium effect size of neurofeedback on alpha asymmetry ($\eta_p^2$ = .16) indicated that a sample of 18 participants should be powered to detect a comparable effect via within-subject ANOVA design we planned to employ [($f = 0.44$, $\alpha = 0.05$, and $\beta = 0.80$)]. Participants were excluded from the experiment if they were left-handed, if they had been diagnosed with dyslexia, with any cardiovascular and/or respiratory diseases, if they had any recent injury or current illness or if they were taking any drug except for the contraceptive pills. Twenty-three right-handed individuals ($n$ = 14 males and $n$ = 11 females) that meet these inclusion criteria, were recruited for the study. One participant was excluded from the analysis because of abnormal electroencephalographic data during the neurofeedback sessions. The final sample size for the analyses comprised 22 (13 males and 9 females) individuals [*M*(*SD*), age 28(9) years, weight 73(17) kg, height 175(10) cm, and maximal oxygen consumption ($\dot{V}O_2$max) 46(9) ml·min·kg$^{-1}$].

The study was approved by the Research Ethics Committee according to the Declaration of Helsinki. Before taking part, participants provided informed consent. Furthermore, prior to attending each visit, they were asked to sleep at least seven hours, avoid heavy exercise and alcohol during the 24 hours preceding each experimental visit, to avoid nicotine and caffeine for the three hours before each experimental visit, and to consume a light meal two hours before attending each visit. Compliance with these instructions was confirmed at the start of every visit. Individuals who reported illness, injury, or non-compliance with the pre-test instructions would have been ineligible to continue.

## Design and Experimental Procedures

The study consisted of a randomised, cross-over, counterbalanced within-subject design. Participants attended three separate laboratory testing visits. The first visit consisted of a preliminary session to confirm participant' eligibility for the study and measure individual maximal oxygen consumption ($\dot{V}O_2$max) via maximal incremental ramp test on the cycle-ergometer. The peak power output (PPO) reached at the end of this test was then used to set the exercise intensity for the following experimental visits. The remaining visits were the experimental conditions; one condition included the neurofeedback to increase relative left frontal cortical activity (NFL), the other condition involved the neurofeedback to increase relative right frontal cortical activity (NFR). Thus, in each experimental visit participants received one of the EEG-neurofeedback interventions in a random and counterbalanced order before the cycling time-to-exhaustion (TTE) test. Each visit was separated by a minimum of 48 hours, and a maximum of 14 days and was conducted in the same laboratory of the School of Sport, Health and Exercise Sciences, Bangor University, under similar and standard environmental condition.

**Preliminary Visit.** First, informed consent was obtained, and demographics and anthropometric data (height and weight) were recorded. Next, participants completed the measures of behavioural activation and inhibition system (BIS/BAS scale) (Carver & White, 1994), approach and avoidance temperament (Elliot & Church, 1997) and a questionnaire to assess their level of physical activity over the past six months and its enjoyment (Motl et al., 2001). After that, participants moved onto the cycle-ergometer (Excalibur Sport, Lode, Groningen, Netherlands) and were asked to perform a maximal incremental ramp test to assess $\dot{V}O_2$max and PPO. The test started with 2 min rest for baseline recording after which the power automatically increased from 50 W (25 W for females) by 25 W every minute until voluntary exhaustion. Verbal encouragement was provided close to the end of the test to ensure that participants reached their maximal effort. During the test, oxygen consumption was measured breath by breath via a computerised metabolic gas analyser (Metalyzer 3B, Cortex Biophysik, Leipzig, Germany) connected to a mouth mask (7600 series, Hans Rudolph, Kansas City, MO, USA). The device was calibrated before each test using a known concentration of gases and a 3 L calibration syringe (Series 5530, Hans Rudolph). Maximal oxygen consumption was defined as the highest value of oxygen uptake averaged over 15 s. During the test, heart rate (HR) was recorded continuously throughout the test with a wireless chest-strap connected to heart rate monitor (RS800CX Polar Electro, Electro, Finland) and rating of perceived effort (RPE) was measured at the end of every incremental stage using the Category Ratio scale (CR-10) developed by Borg (1998). Before starting the maximal incremental ramp test, frame specifications of the cycle-ergometer were adjusted according to participants preferences and recorded for the remaining visits.

**Experimental Visits (2 and 3).** The two experimental visits were identical and lasted approximately two hours each. Upon participant’ arrival, compliance with the instruction was checked and then participants were fitted with Ag/AgCl electrodes (Ambu®) for electroencephalogram (EEG) and electromyogram (EMG) recording (see *Task and Measures*). After instrumentation and instruction participants completed the self-reported measures of mental fatigue, Positive-Negative Affect Schedule (PANAS), State of Self-Control Capacity Scale (SSCCS) and intrinsic-success motivation (see section: *Psychological Measures*). Next, participants sat quietly for 5 min to allow baseline recording of physiological measures, EEG and heart rate variability (HRV) (see section: *Physiological Measures*). Then, they completed a cognitive written task to elicit a state of mental fatigue (see *Cognitive Task*) followed by a second 5-min recording of physiological measures and a second assessment of self-reported mental fatigue, affective state (PANAS), self-control (SSCCS) and motivation. They then received one of the EEG-neurofeedback interventions (NFL or NFR), followed by a final assessment of self-reported mental fatigue, affective state, self-control and motivation. Next, participants moved onto the cycle-ergometer to perform the time to exhaustion cycling test which required them to pedal for as long as possible at an intensity corresponding to the 65% of their PPO (see section: *Cycling Time-to-Exhaustion Test*). Lastly, participants completed a brief interview during which they were asked to recall their attentional focus throughout the cycling time-to-exhaustion test (TTE). At the end of the session, participants were thanked and allowed to leave.

All exercise tests were performed on the same braked cycle-ergometer (Excalibur Sport, Lode, Groningen, Netherlands) set in hyperbolic mode, which allows the power to change independently of pedal cadence (revolution per minute). For all exercise tests, participants were instructed to pedal until voluntarily exhaustion defined as the point at which the individual voluntarily stopped the test, or the cadence had fallen below 60 revolution per minute (rpm) for more than five consecutive seconds. During the tests, participants were asked to remain in the saddle and were allowed to freely choose the cadence between 60 and 100 rpm.

## Manipulations and Measures

### *Cognitive Task*

Before the neurofeedback intervention, participants produced a handwritten copy of a typed piece of text describing physics processes. Importantly, they were instructed to omit any instances of letters *A* and *N* from their handwritten copy. Hence the performer had to override the automated writing habits in order to comply with the instruction. This task was adapted from similar versions previously used to induce a state of cognitive self-control depletion (Myers et al., 2018). In each visit, participants were presented with two different texts to reduce habituation and the texts were randomly allocated based on visit order and condition. Texts consisted of 360 and 352 words and the instances of letters *A* and *N* were 147, 151, and 135 and 112, respectively. Time to complete the task was recorded and performance was assessed as the proportion of *A* and *N* instances not omitted.

### *EEG Neurofeedback Interventions*

The neurofeedback interventions consisted of six blocks of 2 min 30 s with one minute of rest in between each block. During each block, a computer running Bioexplorer software (Cyberevolution, Brainquiry, neuroCare Group) extracted the signal from each lead and simultaneously calculated the alpha frequency power using a fast Fourier transform algorithm with Hanning windowing function. The signal was 8-13 Hz band-pass filtered using the 6th order Butterworth IIR filter and averaged continuously every 5 ms. The resulting values were then fed back to the individuals via bar charts displaying alpha power at the F3 and F4 sites and an auditory tone that changed in pitch with changes in the ratio of F3 and F4 alpha power.

**NFL Group.** For the NFL condition, the tone was set to silence and the colour of the bar changed from red to blue when participants decreased their F3 alpha power by 1.5% and increased their F4 alpha power by 1.5% from their baseline level (blocks 1-3) or when they decreased F3 by 3% and increased F4 by 3% (blocks 4-6). Participants were told that decreasing the height of the F3 bar graph and increasing the height of the F4 bar graph would silence the tone, and their goal was to silence and keep the tone silent for as long as possible.

**NFR Group.** The procedure for the NFR condition was identical, except their goal was to increase the height of the F3 bar and decrease the height of the F4 bar. The tone silenced when participants increased their F3 alpha power and decreased their F4 alpha power by 1.5% (sessions 1-3) and 3% (sessions 4-6) from baseline.

To help ensure the signal was regulated by cognitive processes and was not contaminated by artefacts, the tone was prevented from silencing in both NFL and NFR interventions during any period where there was > 10 µV of 50 Hz activity in the EEG signal.

### *Cycling Time-to-Exhaustion (TTE) Test*

After the neurofeedback intervention, participants completed a TTE test on the cycle-ergometer. The test started with a 3-min warm-up at the intensity corresponding to 30% of individuals' PPO. After the warm-up, the intensity was increased to a power output corresponding to 65% of PPO and participants were instructed to cycle as long as they could. We used the PPO to set the intensity of the TTE test to consider individual differences in fitness level and, based on our previous studies, we expected the exercise at this intensity to last approximately 20 min. Before starting the test, participants were reminded to cycle until exhaustion, to remain sitting in the saddle for the duration of the TTE test and to maintain the cadence between 60 and 110 rpm. No verbal encouragement, or feedback about elapsed cycling time, were provided at any point during the test. HR, muscular activity from the right vastus lateralis and cadence were recorded continuously during the test (see below for details). In addition, RPE (CR-10) and feeling scale (FS) were presented to participants at the end of the warm-up and then at the final 15 s of every minute of the cycling TTE test (see *Psychological*

*Measures* below). Three minutes after the end of the exercise task, a 0.5 μl sample of whole fresh blood was taken from the left earlobe and blood lactate concentration was measured with a portable lactate meter (Lactate Pro 2 LT-1730, Arkray, Shiga, Japan).

### *Physiological Measures*

**EEG recording.** EEG signal was acquired from F3, F4, Fp1 and Fp2 sites with the electrodes attached on the scalp and connected to a DC amplifier (Brainiquiry PET-4, neuroCare) that digitalized the signal at 1000 Hz. The active electrodes were positioned with a stretchable lycra cap in accordance with the 10-20 system (Jasper, 1958) and were referenced to linked mastoids, with a ground electrode positioned at Fpz. Prior to electrodes' attachment, the sites on the scalp were abraded with a blunt needle and a combination of cream (Nuprep, Weaver) and alcohol wipes was used for mastoids sites to reduce skin impedance. Conductive gel (SignaGel, Parker) was applied to all recording sites and electrode impedance at each site was kept below 5 kΩ. Cortical activity was recorded at the beginning of each visit (baseline), after the cognitive task (post CT) and then, during the six neurofeedback blocks. The two resting measures (baseline and post CT) consisted of five 30 s recordings during which participants sat still and maintained their gaze toward a black paper (A5) on the wall. In the first visit, the power within the alpha frequency band (8-13 Hz) was extracted online and averaged over the five baseline recordings and across sites F3 and F4. The resulting value was used to individualise the thresholds for the neurofeedback interventions described above.

**Heart Rate and Heart Rate Variability.** Participants were fitted with a chest strap (H7, Polar Electro) wirelessly connected to the Polar (RS800CX) receiver unit for the measure of R-R intervals. Beat-to-beat heart rate data were recorded at the beginning of each visit (baseline), after the cognitive task (post CT), during the neurofeedback interventions and during TTE test. The two resting measures (baseline and post CT) followed the EEG assessment and consisted of 2 min 30 s continuous recordings during which participants sat still and maintained their gaze toward a black paper (A5) on the wall. Beat-to-beat heart rate data were, then, exported offline to the software Polar Pro Trainer (version 5) and used to derive indices of heart rate variability.

**Electromyographic (EMG) Recording.** Electromyographic (EMG) signal from the vastus lateralis muscle of the right leg was measured continuously during the TTE test. Data were collected using a differential amplifier EMG system, (BIOPAC Systems ©, EMG100C TM amplifier). In accordance with the recommendations from the European SENIAM project (Hermens et al., 2000), two active surface electrodes (universal Ag/AgCl Ambu® BlueSensor R electrodes), with an interelectrode (centre to centre) distance of 2 cm, were placed longitudinally with respect to the underlying muscle fibers arrangement at two-thirds of the distance between the anterior superior iliac spine and lateral border of the patella. The reference was located on the patella. Prior to electrodes attachment the sites were shaved, exfoliated and clean with cream (Nuprep, Weaver) and alcohol wipes. Conductive gel (SignaGel, Parker) was applied to all recording sites and electrode impedance at each site was kept below 10 kΩ. Before commencing the cycling test, the wires connected to the electrodes were secured with tape to reduce movement artefacts. During the TTE test, the EMG signal was amplified with a gain of 500 Hz and filtered at 10-500 Hz and then digitalised online at a sampling frequency of 2 kHz. Time windowed root mean square (RMS) of the vastus lateralis (vl) raw EMG signal was automatically computed by the software at intervals of 30 ms and this continuous signal was used for the analysis.

### *Psychological Measures*

Upon their arrival (baseline), after the cognitive task (post CT) and after the neurofeedback participants completed the following questionnaires:

**Mental Fatigue.** A visual analogue scale was used to measure subjective level of mental fatigue (e.g., Van Cutsem et al., 2017; Mockel et a., 2015). Participants were asked to indicate their current level of mental fatigue by placing a mark on a 10 cm line with two verbal anchors, *not at all mentally fatigued* and *mentally exhausted*.

**Affective State.** Affective state was measured with the short version of the PANAS (Mackinnon et al., 1999). It includes 10 items to be rated from 1 (*not at all*) to 5 (*extremely*); five items are related to positive valence (e.g., “enthusiastic”, “inspired”) and five to the negative (e.g., “afraid”, “upset”). For each assessment, participants were instructed to rate each item based on how they felt at that moment in time. For each subscale the final score consisted of the sum of its items.

**State of Self-Control Capacity Scale (SSCCS).** To check the effectiveness of the cognitive written task, cognitive depletion was measured with the short version of the State of Self-Control Capacity Scale (SSCCS). The scale includes 10 items rated on a 7-point Likert-type scale from 1 (*not true*) to 7 (*very true*). For each assessment, participants were instructed to answer each item based on how they felt at that moment in time. The items were summed to compute the final score for statistical analysis and higher values were representative of a greater state of self-control (no depletion) while lower values indicated a greater state of depletion. This scale has been previously used to assess the self-control state in ego-depletion research (e.g., Graham et al., 2017).

**Intrinsic-Success Motivation.** Motivation toward the TTE test was measured with the scale developed by Matthews et al. (2001). It includes 15 items; 7 items refer to success motivation, other 7 items refer to intrinsic motivation and one question assesses general motivation (“I’m motivated to do the task”). For each subscale the mean score was used for statistical analysis. The questionnaire has been previously used to assess motivation toward task in the context of endurance performance (e.g., Marcora et al., 2009).

### *In-task Psychological Measures*

**Rating of Perceived Effort (RPE) and Affect.** Perception of effort and affective state during the exercise were measured with the CR-10 scale (Borg, 1998) and the feeling scale (FS) (Hardy & Rejeski, 1989), respectively. Scales were presented one after the other to the participants at the end of the warm-up and, then, during the final 15 s of every minute until exercise was terminated. The standard instructions of the scale were provided in visit 1 prior to starting the maximal incremental ramp test and low and high anchor points were established using the procedures advocated by Noble and Robertson (1996). Participants were instructed to indicate how hard, strenuous and heavy the exercise felt at that moment (Marcora, 2010) on the rating of perceived effort CR-10 scale. Prior to each cycling TTE test, participants were reminded of these instructions. For the FS, participants were instructed to report their affect on the 11-points bipolar scale in accordance with the standard instruction of the scale (see Hardy & Rejeski, 1989). The scale ranges from + 5 (*very good*) to -5 (*very bad*) with verbal anchors provided at the 0 point (*neutral*) and then at all odd integers (Hardy & Rejeski, 1989). The FS was used to determine whether the affective responses elicited with the exercise was influenced by the neurofeedback interventions.

### *Post-task Psychological Measures*

**Attentional Focus.** Attentional focus during the cycling TTE test was assessed with a brief interview developed by Brick et al. (2016). Using an 11-point Likert type scale ranging from 0 (*never*) to 10 (*always*), participants rated how frequently their attention had focused on thoughts from each of the following categories: internal sensory monitoring, active self-regulation, outward monitoring, and distraction. Brick et al. (2014) constructed these categories to expand the two-dimensional classification (associative and dissociative thoughts) originally developed by Stevinson and Biddle (1998). *Internal sensory monitory* reflects thoughts associated with physical sensations such as feelings of fatigue, thirst, muscle soreness. *Active* *self-regulation* refers to self-regulatory instructions that actively monitor and control actions, feeling and thoughts such focus on technique, cadence, or relaxing. *Distraction* includes voluntary and/or involuntary thoughts not related to the exercise task such as reflective thoughts, daydreams, imagining music etc. Lastly, *outward monitoring* refers to thoughts directed to external and/or environmental cues associated with the exercise task. Because participants did not receive any feedback and information during the TTE test, this last scale was not included. For each category, explicative information was provided to assist participants to recall their thoughts.

**Intrinsic Motivation Inventory**. Task-enjoyment and task-importance were measured at the end of the TTE test in each condition with the intrinsic motivation inventory (McAuley et al., 1989; Kelly et al., 2017). Based on our theoretical framework, we used enjoyment/interest and importance/effort subscales of the inventory. The first is composed of seven items and considered the self-reported measure of intrinsic motivation; the latter consisted of five items, four items effort-related (e.g., “I put a lot effort into this activity”, “I did not try very hard to well at this activity”) and one covers importance (“It was important to me to do well at this task”). Participants made their responses on a 7-point Likert scale from *not at all true* to *very true*.

### *Data Reduction*

**EEG**. Matlab (R2019a) was used to extract EEG data recorded at rest and during the neurofeedback for statistical analyses. The signal from F3, F4, Fp1 and Fp2 was down-sampled offline at 256 Hz, and a 1 Hz high pass filter (cut off frequency 0.8 Hz and transition bandwidth 0.4 Hz), and 30 Hz low pass filter (cut off frequency 35 Hz and transition bandwidth 10 Hz), were applied. Continuous EEG data were manually corrected for eyes blinks artefacts. Time-series data were divided into 2 s epochs (75% overlap) and epochs containing voltage shifts greater than ± 75 μV were rejected. The resulting data segment were tapered using a

Hanning window and fast Fourier transformation with a spectral resolution of 0.5 Hz was used to compute the power in the retained epochs. For each recording, power within theta (4-7 Hz), alpha (8-13 Hz) and beta (14-20 Hz) frequencies were averaged across epochs. Resting measures of theta band power (baseline and after CT) were used as an index of mental fatigue (see Van Cutsem et al., 2017). The values of alpha power gauged from each recording were then used to compute the index of hemispheric asymmetry defined as the log-transformed alpha power of right leads (F4 or Fp2) minus the log-transformed alpha power of left leads (F3 or Fp1), e.g. Ln (alphaF3) – Ln (alpha F4) (Smith et al., 2017).

**HR and HRV**. Beat-to-beat heart rate data of each 2 min 30 sec recording were analysed with the Kubios software (Kubios HRV Analysis 3.3.1, University of Eastern Finland, Kuopio). Prior to the analysis, artefacts were corrected with beat removal and linear interpolation with adjacent values using the thresholds correction algorithm available within the software. Any recordings that required more than 5% of the beats to be corrected were considered to contain excess noise and were thereby discarded. This occurred for five participants that were excluded from the analysis. For the time-domain analysis, heart rate and root mean square of differences between adjacent normal RR intervals (RMSSD) were computed and log-transformed RMSSD (log-RMSSD) were used for the analysis (Task force, 1996). For frequency domain analysis, power spectrum density (PSD) of the inter-beat intervals was estimated via Fast Fourier Transform; RR intervals were resampled at 256 Hz and PSD was determined with Welch’s periodogram method with a window width of 75 s and 50% overlap. Smoothness priors’ method was applied with lambda set to 500 resulting in the cut-off frequency of 0.035 Hz (Tarvainen et al., 2002). Absolute power (ms$^2$) was calculated in the two main bands, high frequency (HF: 0.04 – 0.15 Hz) and low frequency (LF: 0.15 – 0.40 Hz) and log-transformed values (log-HF and log-LF) were then used for the analysis. RMSSD and

HF were chosen as an indicator of cardiac vagal tone and thus an index of parasympathetic activity (Laborde et al., 2017; Task force, 1996).

**In-task Psychological and Physiological Measures.** To assess temporal changes of physiological (HR and RMS-vl root mean squared of the vastus lateralis EMG signal) and psychological measures (RPE and FS) recorded during the TTE tests, the total time of each TTE test was divided into five time-points, namely the end of the first full minute and the minutes corresponding to the 25, 50, 75 and 100%. The values of RPE and FS recorded at those 5 time-points were used for the statistical analyses and 1-min average was computed for HR and RMS-vl and used for the analyses.

To provide further insight into the time-responses of HR, RMS-vl and RPE variables, we computed the area under the curve (AUC) for HR, RMS-vl and RPE using the integrated trapezoid formula (Pruessner et al., 2003). For each individual TTE, the trapezoid areas were calculated from the values of each variable attained at the minutes corresponding to the 25%, 50%, 75%, 100% of the total time to exhaustion test and the time distance between these points, e.g., $\mathrm{AUC}_{\mathrm{RPE}} = (\mathrm{RPE}_{\mathrm{i}} + \mathrm{RPE}_{\mathrm{i+1}}) \cdot t_i/2$

where *i* = height at the start of the quartile, *i+1* = height at the end of the quartile, and $t_i$ = duration (length) of the quartile (Pruessner et al., 2003).

## Statistical Analysis

**Primary Analyses.** To determine the effect of the cognitive task we run 2 (Condition; NFL and NFR) × 2 (Task; baseline and after cognitive task) repeated measures ANOVAs on measures of mental fatigue and state of self-control and repeated measures MANOVAs on the EEG data (power of theta, alpha and beta band frequencies and alpha asymmetry value across the four electrodes position). Then, we assessed the effect of the neurofeedback interventions on alpha asymmetry values derived from each neurofeedback block with 2 (Condition) × 6 (Block of neurofeedback 1 to 6) repeated measures ANOVA. Paired sample *t*-tests assessed the effect of the neurofeedback interventions on self-reported measures of mental fatigue and self-control before the TTE test, TTE-related variables, i.e., total time, rating of task-enjoyment, task-importance and attentional focus and AUCs drawn from HR, RMS-vl and RPE. Paired sample *t*-tests also compared the values of RPE, HR, FS, blood lactate at exhaustion. Lastly, 2 (Condition; NFL and NFR) × 5 (Time; 1-min, 25%, 50%, 75% and 100% of TTE) repeated measures ANOVAs were performed on in-task measures of HR, RMS-vl, RPE and FS.

**Secondary Analyses**. Baseline measures of the psychological questionnaires (mental fatigue, SSCSS, PANAS, motivation) and physiological variables (alpha asymmetry, HR and HRV data), were subjected to paired sample *t*-test to control for any baseline differences between the two conditions. Two (Condition; NFL and NFR) × 8 (Task; baseline, after CT and 6 neurofeedback blocks) repeated measures ANOVAs were run on HR and HRV data (log-RMSSD, log-HF and log-LF) to assess temporal changes induced with the neurofeedback manipulation and compare the two interventions. We employed separate 2 (Condition; NFL and NFR) × 4 (Task; baseline, after cognitive task and after intervention) repeated measures ANOVAs to examine the effect of the cognitive task and the neurofeedback interventions on reported measures of affective state and motivation.

Significant interaction effects were investigated with orthogonal contrasts. For all analyses, statistical significance was set at $p \leq 0.05$ and effect sizes were estimated with Cohen’s $d_{av}$ calculated with the average standard deviation and corrected as Hedges’s $g_{av}$ (see Formula 10, Lakens, 2014) and partial eta squared ($\eta_p^2$) for F-tests. All the analyses were performed using SPSS (v. 25, IBM, Chicago, IL).

# Results

## Primary Analyses

### *Effect of the Cognitive Task*

Time to complete the cognitive writing task was 19 min 36 s (*SD* = 4 min 39 s) and 19 min 5 s (*SD* = 4 min 03 s) in NFL and NFR, respectively; task-error (proportion of the total number of letters not omitted) was 0.05 (*SD* = 0.06) in each condition. Altogether this suggested that participants were engaged similarly in the tasks across the two visits. Two × 2 repeated measures ANOVA revealed that the cognitive task reduced state of self-control significantly ($F(1,21)=4.41$, $p=.048$, $\eta_p^2=.173$) and increased self-reported mental fatigue significantly ($F(1,21)=7.90$, $p=.010$, $\eta_p^2=.273$). This result indicated that the cognitive task successfully induced a state of cognitive depletion with no difference between condition (effect of condition: $p=.733$ and $p=.956$ for SSCCS and mental fatigue, respectively). Repeated measures MANOVAs showed that the written task did not influence significantly alpha-band ($\Lambda=.816$, $F(4,18)=1.02$, $p=.425$) and beta-band power ($\Lambda=.979$, $F(4,18)=.10$, $p=.982$), and alpha asymmetry scores ($\Lambda=.976$, $F(2,20)=.24$, $p=.787$). However, there was a significant effect of cognitive task on theta-band power which increased significantly after the task ($\Lambda=.522$, $F(4,18)=4.11$, $p=.015$). There were no differences between conditions in any measure. Follow up with repeated measures ANOVAs showed that power of theta frequency band increased at each site. Table 1 reports theta, alpha and beta bands power and alpha asymmetry values at baseline and after the written task.

**Table 1**

*Theta, Alpha, Beta Bands and Alpha Asymmetry Power ($\mu V^2/Hz$) at Baseline and After the Cognitive Task*

| Frequency | | Baseline | Post cognitive task | ANOVA | | |
|---|---|---|---|---|---|---|
| | | *M (SE)* | *M (SE)* | *F* | *p* | $\eta_\rho^2$ |
| Theta (4-7Hz) | | | | | | |
| | F3 | 0.819 (0.086) | 0.872 (0.087) | 3.996 | .059 | .160 |
| | F4 | 0.852 (0.074) | 0.914 (0.071) | 18.021 | .000 ↑ | .462 |
| | Fp1 | 1.146 (0.189) | 1.288 (0.195) | 4.971 | .037 ↑ | .191 |
| | Fp2 | 1.160 (0.209) | 1.303 (0.221) | 6.485 | .019 ↑ | .236 |
| Alpha (8-13Hz) | | | | | | |
| | F3 | 0.649 (0.079) | 0.660 (0.059) | .061 | .807 | .003 |
| | F4 | 0.670 (0.085) | 0.693 (0.067) | .231 | .636 | .011 |
| | Fp1 | 0.643 (0.072) | 0.671 (0.052) | .500 | .487 | .023 |
| | Fp2 | 0.650 (0.075) | 0.685 (0.057) | .780 | .387 | .036 |
| Beta (14-20Hz) | | | | | | |
| | F3 | 0.400 (0.049) | 0.403(0.049) | .019 | .892 | .001 |
| | F4 | 0.377 (0.041) | 0.373 (0.040) | .014 | .906 | .001 |
| | Fp1 | 0.454 (0.063) | 0.447 (0.061) | .089 | .768 | .004 |
| | Fp2 | 0.410 (0.039) | 0.408 (0.036) | .009 | .925 | .000 |
| Alpha Asymmetry | | | | | | |
| | lnF4 – lnF3 | 0.023 (0.042) | 0.037 (0.043) | .508 | .484 | .024 |
| | lnFp2 – lnFp1 | 0.009 (0.022) | 0.013 (0.019) | .115 | .738 | .005 |

*Note*. 2 × 2 repeated measures ANOVAs, *M* = Marginal Means for factor task averaged across condition, degree of freedom = 1 and 21, *N* = 22.

↑ significant increase

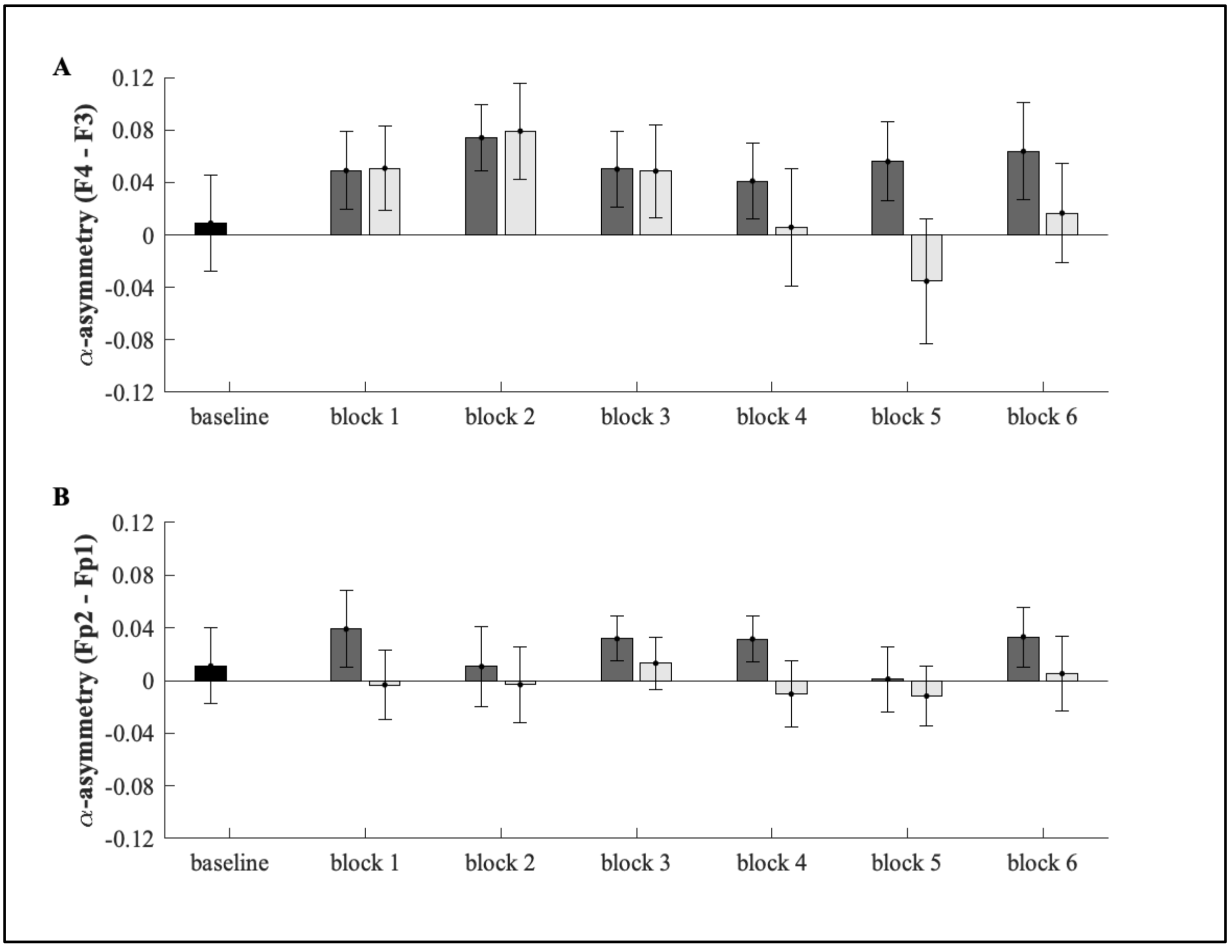
### *Effect of the Neurofeedback Interventions*

**Alpha Asymmetry**. During the EEG-neurofeedback to increase relative right cortical activity (NFR), alpha asymmetry scores tended to be lower compared to the values of the NFL intervention, especially during the last three blocks when the threshold of the feedback was higher (i.e., ± 3%). However, the two-way ANOVA performed on alpha asymmetry (lnF4 - lnF3) during the neurofeedback blocks did not report a significant main effect condition ($F(1,21)=.60$, $p=.448$, $\eta_\rho^2=.028$), and Condition × Block interaction, ($F(3,72)=1.27$, $p=.290$, $\eta_\rho^2=.057$). To examine the effect of the neurofeedback thresholds frontal alpha asymmetry (lnF4 – lnF3) values were subjected to a three-way ANOVA with condition (NFL and NFR), threshold (± 1.5% and ± 3%) and block (1 to 3) as within-subject factors. Results showed a significant main effect of threshold ($F(1,21)=4.99$, $p=.036$, $\eta_\rho^2=.192$), however, the interaction Condition × Threshold was not significant ($F(1,21)=3.50$, $p=.076$, $\eta_\rho^2=.143$).

The 3-way ANOVA performed on alpha asymmetry computed from lnFp2 - lnFp1 revealed no significant main effects ($p$-values$\geq .184$) and interactions ($p$-values$\geq .403$). These results suggested that the effect of the neurofeedback was specific for the trained sites (i.e., F3 and F4). That is, the neurofeedback interventions modified frontal alpha asymmetry in the sites used to provide the signal feedback (i.e., F3 and F4). Figure 1 showed alpha asymmetry scores for each site at baseline and during the 6 neurofeedback blocks.

**Figure 1**

*Frontal Alpha Asymmetry Baseline and during the Six Neurofeedback Blocks*

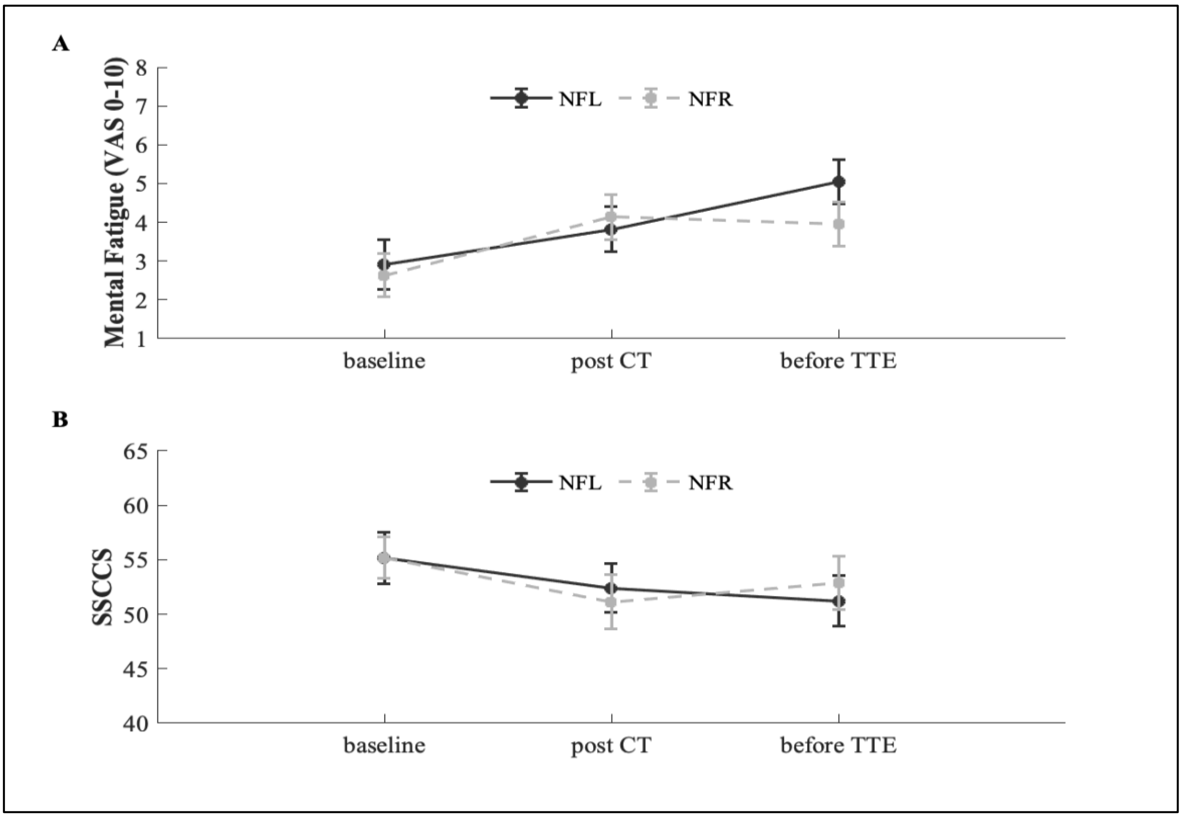


*Note. M* ± *SE*. Panel A: effect of neurofeedback on alpha asymmetry in the trained location (F3 and F4). Panel B: effect of neurofeedback on alpha asymmetry in other location (Fp1 and Fp2). Positive asymmetry scores indicate greater relative left than right cortical activity, while negative scores represent greater relative right over left cortical activity. Black: baseline values; Grey: NFL condition; Light Grey: NFR condition.

**Mental Fatigue and Self-Control**. Paired sample *t*-tests on SSCCS revealed no significant difference between conditions (*t*(21)=-.94, *p*=.356, $g_{av}$=.144). Mental fatigue was higher after the NFL intervention compared to after the NFR intervention (*t*(21)=2.03, *p* =.056, $g_{av}$=.398). Means (*SD*) were 5.05 (2.68) and 3.95 (2.70) for NFL and NFR, respectively. Hence, participants started the TTE with slightly greater mental fatigue after the NFL compared to the NFR intervention.  Figure 2 shows mental fatigue and state of self-control ratings over the visits in the two conditions.

**Figure 2**

*Mental fatigue and State of Self-Control Capacity Scale*



*Note*. *M* ± *SE*. Panel A: Mental fatigue VAS scale measured at baseline, after the cognitive task and before the TTE in each condition. Panel B: State of Self-Control Capacity Scale recorded at baseline, after the cognitive task and before the TTE in each condition. SSCCS = state of self-control capacity scale.

**TTE Performance and Variables at Exhaustion.** TTE tests did not differ between conditions ($t(21)=.28$, $p=.781$, $g_{av}=.025$). Means (*SD*) were 1091s (647) and 1074s (629), for NFL and NFR TTE test, respectively. RPE, HR measured at exhaustion and blood lactate level post-TTE test were not significantly different between conditions ($p \geq .300$) suggesting that participants reached in both conditions a maximal, similar level of effort.

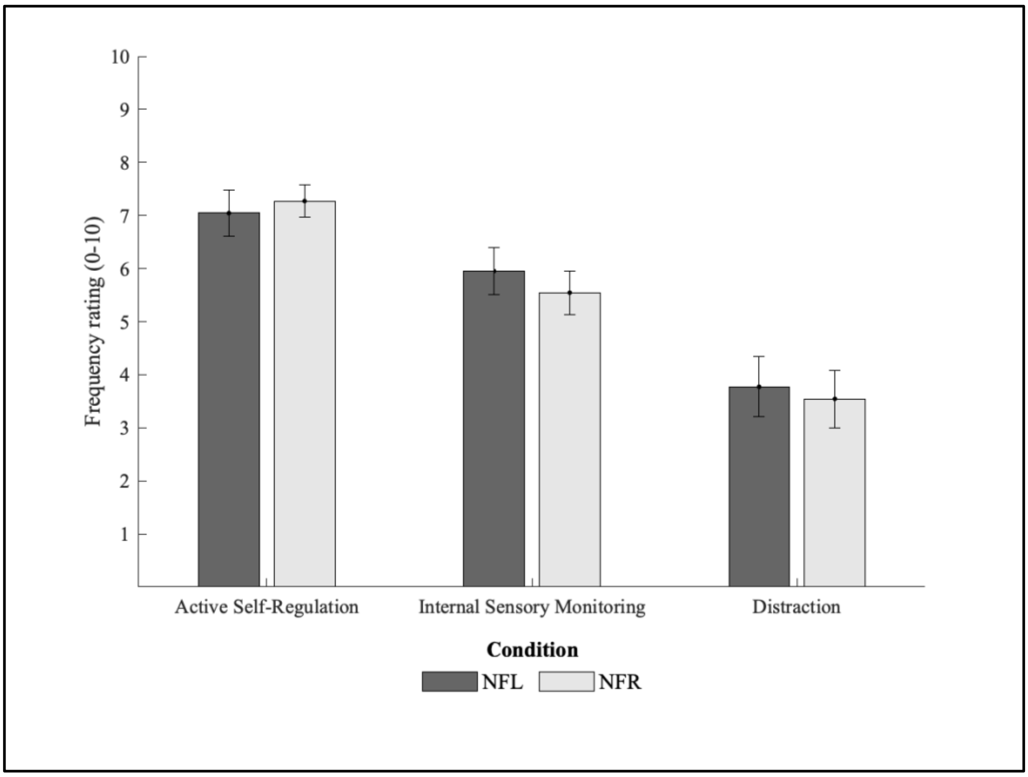
***In-Task RPE and FS.*** RPE during TTE tests did not differ significantly between conditions at any time (main effect: $F(1,21)<.001$, $p=1.00$, $\eta_\rho^2<.000$ and Condition × Time interaction: $F(4,84)=.67$, $p=.616$, $\eta_\rho^2=.031$). As expected, RPE reported a significant main effect of time ($F(3,55)= 230.70$, $p<.001$, $\eta_\rho^2=.917$), increasing linearly throughout the test until its maximal value ($p<.001$ for every level of repeated contrasts). Also AUCs drawn from RPE values during the TTE tests did not differ significantly between conditions ($t(21)=.30$, $p=.765$, $g_{av}=.033$). The FS during TTE tests did not differ significantly between conditions at any time (main effect: $F(1,21)=1.55$, $p=.227$, $\eta_\rho^2=.069$ and Condition × Time interaction: $F(3,64)=1.32$, $p=.274$, $\eta_\rho^2=.059$). However, FS reported a main effect of time ($F(2,39)=41.21$, $p<.001$, $\eta_\rho^2=.662$). Repeated contrasts showed that FS decreased linearly as effort increased ($p$-values$\leq .010$ for all levels of repeated contrasts after 25% of TTE).

***In-Task RMS-vl and HR.*** Repeated measures ANOVA on muscular activity (RMS-vl) did not show significant main effects (condition: $F(1,21) = 1.00$, $p=.328$, $\eta_\rho^2=.046$; and time: $F\ (1,24)=1.40$, $p=.253$, $\eta_\rho^2=.063$) and interaction ($F(1,31)=1.70$, $p=.203$, $\eta_\rho^2\ =.075$). Accordingly, the AUCs drawn from RMS-vl values did not differ significantly between conditions ($t(21)=-1.08$, $p=.293$, $g_{av}=.199$). Likewise, HR was not different between condition ($F(1,20)=.27$, $p=.606$, $\eta_\rho^2=.014$). However, as expected HR increased during the TTE test ($F(2,36)=240.91$, $p<.000$, $\eta_\rho^2=.923$), and repeated contrasts revealed that it increased significantly at every time point ($p$-values<.000). AUCs drawn from HR values during the TTE tests did not differ significantly between condition ($t(20)=.133$, $p=.896$, $g_a=.012$).

***Post-Task Attentional Focus and IMI.*** Paired sample *t*-tests revealed no significant differences between condition in frequency of thoughts related to active self-regulation (*t*(21)=-.540, *p*=.595, $g_{av}$=.128), internal body sensations (*t*(21) =.833, *p*=.414, $g_{av}$= .200), and distraction (*t*(21)=.389, *p*=.701, $g_{av}$=.086). Figure 3 displays the frequencies of attentional focus during the TTE in each condition and Table 2 reports the results from the McNemer test. The neurofeedback interventions did not influence significantly the enjoyment subscale of IMI, means (*SD*) in NFL: 5.28(1.73) and NFR: 5.17(1.15) (*t*(21)=1.07, *p*=.298). Also, importance was not rated differently between conditions, NFL: 6.34(0.74) and NFR: 6.39(0.71) (*t*(21)=-.436, *p*=.667).

**Figure 3**

*Attentional Focus Frequency Rating in Each Condition*



*Note*. The figure displayed the values of the frequency of thoughts pertaining to each attentional focus category in the two conditions

**Table 2**

*Frequencies (% of Individuals) and Test Statistics for Specific Thoughts of Attentional Focus as a Function of the Neurofeedback Intervention.*

| Attentional Focus Categories | Condition | | McNemer Test |
|---|---|---|---|
| | NFL % | NFR % | *p* |
| Active Self-Regulation | | | |
| Cycling Cadence | 91 | 77 | .250 |
| Cycling Technique | 68 | 77 | .687 |
| Control Breathing Frequencies | 64 | 64 | 1.00 |
| Motivational Self-Talk | 59 | 68 | .687 |
| Cognitive Strategies | 45 | 50 | 1.00 |
| Relaxation (e.g., meditation) | 27 | 32 | 1.00 |
| Internal Sensory Monitoring | | | |
| Muscular sensations (e.g., soreness, pain) | 86 | 82 | 1.00 |
| Body feelings and sensations (e.g., thirsty, temperature, skin wetness) | 86 | 77 | .625 |
| Fatigue and Tiredness | 77 | 77 | 1.00 |
| General Effort | 73 | 73 | 1.00 |
| Body discomfort (e.g., position) | 55 | 73 | .219 |
| Breathing and heart rate discomfort (e.g., breathless) | 50 | 55 | 1.00 |
| Distractive Thoughts | | | |
| Reflective thoughts | 32 | 55 | .125 |
| External cues (e.g., laboratory objects) | 41 | 36 | 1.00 |
| Daydreaming | 32 | 18 | .375 |
| Switching off | 23 | 41 | .219 |

*Note*. NFL = increase relative left cortical activity; NFR = increase relative right cortical activity; % percentage of participants adopting the thought listed; *p* = exact p-values.

## Secondary Analyses

### *Baseline Measures*

Self-reported measures (SSCCS, mental fatigue, PANAS and motivation) recorded at baseline did not differ between conditions (*p*-values>.20). Similarly, baseline measures of frontal alpha asymmetry (*p*=.993), HR (*p*=.968), log-RMSSD (*p*=.397), log-HF (*p*=.580) and log-LF (*p*=.572) were not significantly different between conditions. This confirmed that on average participants started each experimental session in a similar psychological and affective state. Table 3 reports descriptive and test statistics of these baseline measures.

### *HR and HRV*

Two-way ANOVA reported a significant main effect of task on HR ($F$ (3,43)=8.97, $p$<.001, $\eta_\rho^2$=.359). Follow-up with repeated contrasts showed that both baseline and post cognitive task HR were significantly higher compared to HR recorded during the neurofeedback ($F$(1,16)=18.38, $p$=.001, $\eta_\rho^2$=.535 and $F$(1,16)=12.62, $p$=.003, $\eta_\rho^2$=.441, respectively). Furthermore, HR was lower in the first neurofeedback block compared to the following blocks ($F$(1,16)=12.81, $p$=.003, $\eta_\rho^2$=.445), then it remained constant throughout (*p*-values>.100). However, it was not significantly affected by the type of neurofeedback (main effect of condition: $F$(1,16)=.485, $p$=.496, $\eta_\rho^2$=.029 and Condition × Task interaction: $F$(3,55)=.885, $p$=.467, $\eta_\rho^2$=.052). On the contrary, factorial ANOVA on log-RMSSD, log-HF and log-LF did not report significant main effects or significant interaction. HR and HRV data of each 2 min 30 s recording are reported in Table 4.

**Table 3**

*Descriptive and Test Statistics for Baseline Measures as a Function of Condition.*

| Variables | Condition | | paired *t*-tests | | |
|---|---|---|---|---|---|
| | NFL | NFR | | | |
| | *M (SD)* | *M (SD)* | *t (df)* | *p* | $g_{av}$ |
| SSCCS | 55.14 (11.10) | 55.18 (8.84) | - .02 (21) | .984 | .004 |
| Mental Fatigue VAS | 2.91 (2.97) | 2.64 (2.59) | .45 (21) | .660 | .096 |
| Positive affect (PANAS) | 15.82 (3.62) | 15.55 (3.17) | .41 (21) | .689 | .079 |
| Negative affect (PANAS) | 6.55 (2.69) | 6.68 (2.75) | - .48 (21) [a] | .632 [a] | .102 [a] |
| Intrinsic Motivation | 22.18 (3.07) | 23.00 (2.88) | - 1.32 (21) | .201 | .270 |
| Success Motivation | 16.91 (4.35) | 17.32 (5.08) | - .60 (21) | .555 | .085 |
| Alpha asymmetry | | | | | |
| (lnF4 - lnF3) | 0.022 (0.245) | 0.023 (0.166) | - .01 (21) | .993 | .001 |
| (lnFp2 – lnFp1) | 0.006 (0.133) | 0.012 (0.104) | - .23 (21) | .822 | .047 |
| Heart rate data [b] | | | | | |
| RR (ms) | 1035 (184) | 1034 (189) | .02 (20) | .983 | .002 |
| Log-RMSSD | 4.01 (0.50) | 4.11 (0.58) | - .86 (20) | .397 | .192 |
| Log-HF | 6.93 (1.04) | 6.77 (1.46) | .56 (20) | .580 | .121 |
| Log-LF | 6.75 (0.91) | 6.92 (1.03) | - .57 (20) | .572 | .167 |

*Note*. NFL = increase relative left cortical activity; NFR = increase relative right cortical activity; SSCCS = state of self-control capacity scale; RR = RR interval; Log-RMSSD = log transformed root mean square of the successive differences; Log-HF = log transformed high frequency component power (RR power spectrum); Log-LF = log transformed low frequency component power (RR power spectrum).

[a] *z, p* and *r* Wilcoxon Test

[b] *N* = 21 (missing one data due to equipment problem)

**Table 4**

*Heart Rate Data Recorded at Rest and during Neurofeedback Blocks in each Condition*

| Variable | | Task | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Baseline | Post CT | Block 1 | Block 2 | Block 3 | Block 4 | Block 5 | Block 6 |
| | | *M* | *M* | *M* | *M* | *M* | *M* | *M* | *M* |
| | | *(SD)* | *(SD)* | *(SD)* | *(SD)* | *(SD)* | *(SD)* | *(SD)* | *(SD)* |
| RR (ms) | | | | | | | | | |
| | NFL | 993$^{*}$ | 1025$^{*}$ | 1075$^{*}$ | 1047 | 1029 | 1055 | 1056 | 1046 |
| | | (160) | (157) | (136) | (146) | (149) | (142) | (159) | (149) |
| | NFR | 987$^{*}$ | 1025$^{*}$ | 1059$^{*}$ | 1024 | 1042 | 1042 | 1053 | 1053 |
| | | (176) | (178) | (163) | (182) | (173) | (178) | (170) | (186) |
| Log-RMSSD | | | | | | | | | |
| | NFL | 3.90 | 3.95 | 4.07 | 4.17 | 3.93 | 4.20 | 4.26 | 4.13 |
| | | (0.47) | (0.44) | (0.48) | (0.62) | (0.48) | (0.60) | (0.59) | (0.52) |
| | NFR | 4.07 | 4.12 | 4.18 | 4.13 | 4.14 | 4.15 | 4.13 | 4.12 |
| | | (0.59) | (0.61) | (0.65) | (0.62) | (0.58) | (0.66) | (0.64) | (0.65) |
| Log-HF | | | | | | | | | |
| | NFL | 6.71 | 6.81 | 6.90 | 6.85 | 6.42 | 6.69 | 7.13 | 6.74 |
| | | (0.95) | (1.06) | (1.23) | (1.21) | (1.08) | (1.21) | (1.09) | (1.36) |
| | NFR | 6.61 | 7.16 | 7.08 | 6.53 | 6.83 | 7.05 | 6.98 | 6.99 |
| | | (1.53) | (1.26) | (1.21) | (1.33) | (1.44) | (1.36) | (1.31) | (1.18) |
| Log-LF | | | | | | | | | |
| | NFL | 6.72 | 6.75 | 6.96 | 7.24 | 6.66 | 7.11 | 7.71 | 7.17 |
| | | (0.87) | (1.11) | (1.33) | (1.70) | (1.27) | (1.50) | (1.46) | (1.54) |
| | NFR | 7.01 | 7.24 | 7.02 | 7.07 | 6.76 | 7.28 | 7.18 | 7.27 |
| | | (0.99) | (0.82) | (1.21) | (1.18) | (1.07) | (1.00) | (1.35) | (0.86) |

*Note*. Task: baseline, after the cognitive task (Post CT) and 6 neurofeedback blocks (Block 1 to 6); NFL = increase relative left cortical activity; NFR = increase relative right cortical activity; Post CT = after cognitive task; RR = RR interval; Log-RMSSD = log transformed root mean square of the successive differences; Log-HF = log transformed high frequency component power (RR power spectrum); Log-LF = log transformed low frequency component power (RR power spectrum).

*N* = 17 (due to the low signal quality data of 5 individuals have been excluded from the analysis).

* significantly different compared to the following recording values.

### *Psychological Questionnaires*

Affective state was not significantly influenced by the neurofeedback interventions. Two-way ANOVA on positive affect schedule did not report significant main effect of condition ($F(1,21)=.103$, $p=.752$, $\eta_{\rho}^2=.005$), and Condition × Task interaction ($F(1,28)=.188$, $p=.735$, $\eta_{\rho}^2=.009$). Furthermore, positive affect did not change significantly throughout the visits (main effect of task: $F(2,42)=.728$, $p=.489$, $\eta_{\rho}^2=.034$). Negative affect schedule was subjected to a Wilcoxon Signed Ranked Test that showed no differences between conditions after the written task ($z=-.422$, $p=.673$) or after the neurofeedback intervention ($z=-.105$, $p=.917$). Similarly, 2-way ANOVA did not report significant main effect of condition in intrinsic ($F(1,21)=1.03$, $p=.321$, $\eta_{\rho}^2=.047$), and success motivation ($F(1,21)=.624$, $p=.439$, $\eta_{\rho}^2=.029$). The main effect for task on success motivation was not significant ($F(2,42)=1.28$, $p=.290$, $\eta_{\rho}^2=.057$), whereas it was significant for intrinsic motivation ($F(2,42)=3.22$, $p=.050$, $\eta_{\rho}^2=.133$). Repeated contrasts showed that ratings of intrinsic motivation at baseline (NFL: $M=22.18$, $SD=3.01$ and NFR: $M=23.00$, $SD=2.88$) tended to be higher than after cognitive task (NFL: $M=21.45$, $SD=3.5$ and NFR: $M=22.09$, $SD=4.14$; $p=.067$, $\eta_{\rho}^2=.151$). However, they did not change after the neurofeedback intervention (NFL: $M=21.41$, $SD=4.38$ and NFR: $M=21.32$, $SD=4.66$). The interaction Condition × Task was not significant for any scale ($p$-values>.344). In general, self-reported measures of motivation and valence were not influenced by intervention, however intrinsic motivation declined after the cognitive task.

# Discussion

Built on the previous investigation (Mottola et al., 2021), the current study implemented the same neurofeedback intervention and examined the mechanisms underlying the effect of EEG-neurofeedback to modify frontal cortical asymmetry on whole-body endurance performance following a fatiguing cognitive task. Mottola et al. (2021) were the first to find a beneficial effect of neurofeedback to increase relative-left frontal cortical activity on endurance performance.

## *Effect of Neurofeedback on Performance under Mental Fatigue*

In the present study, however, the increase relative left frontal cortical activity neurofeedback intervention did not improve the TTE test performance significantly. The divergent findings of the two studies could be related to the less pronounced effect of neurofeedback on cortical activity. Accordingly, Mottola et al. (experiment 1B) found a main effect of neurofeedback on frontal alpha asymmetry ($\eta_\rho{}^2 = .16$), meaning that the differences in frontal alpha asymmetry were elicited across the 6 neurofeedback blocks. Whereas, in the present study the same intervention elicited a distinct alpha asymmetry pattern only in the last three blocks of the neurofeedback intervention, when the threshold to increase/decrease alpha values was higher, i.e., set to ± 3% of baseline value compared to ±1.5%.

An additional explanation for the divergent performance findings could be the slightly greater level of mental fatigue found in the NFL compared to NFR before the TTE tests. In each condition, prior to the neurofeedback interventions, participants performed a cognitive depleting task which resulted in a mild state of mental fatigue as indicated by subjective feeling and increased theta power (see Wascher et al., 2014) which was similar in the two conditions. When individuals started the TTE test, subjective feeling of mental fatigue however was slightly higher in NFL condition compared to NFR. Although this result was unexpected, it is possible that the exacerbated feeling of mental fatigue after NFL intervention partly accounted for the dampened effect of neurofeedback to increase relative left cortical activity on TTE test performance. It should be noted however that in Mottola et al. (2021 Experiment 1A) the neurofeedback intervention to increase left-frontal cortical activity benefitted endurance exercise performance when compared to a condition where participants sat quietly and rest, i.e., in spite of the self-regulatory resources required by the neurofeedback training. Consequently, it is likely that in the current study, subjective feeling of mental fatigue accumulated throughout the visit independently from the interventions (see for example Francis et al., 2018).

### *Effect of Neurofeedback on Cortical Activity*

Our results only partly supported the use of neurofeedback intervention to modify frontal alpha asymmetry. Accordingly, we found a medium effect size ($\eta_\rho^2 = .143$) when we introduced the factor threshold to the analysis. In accordance with our results, Mottola et al. (2020) reported a significant difference in alpha asymmetry in blocks 4 and 5 of the neurofeedback intervention when a higher threshold was employed. Although the two studies implemented the same interventions, it is possible that psychological factors such as engagement, effort and control over the cortical activity could influence cortical response to the neurofeedback (Alkoby et al., 2019). Ultimately, these factors can affect the efficacy of the intervention on the neurophysiological target and behavioural outcomes (see Alkoby et al., 2019). In the current study, alpha asymmetry scores during the NFR intervention reached negative values only in the 5th block. Consistently with this, during the NFL intervention, 15 individuals were able to increase alpha asymmetry toward more positive values. On the contrary, in the NFR intervention, only five individuals were able to reduce alpha asymmetry toward more negative values when the threshold was set at ±1.5% and 8 individuals when the threshold was ±3%. This suggests that the thresholds chosen may not be always appropriate to induce a significant shift in relative right frontal cortical activity.

Previous investigations on EEG-neurofeedback to modify frontal alpha asymmetry adopted different protocols and criterion to determine the feedback. For example, Allen et al. (2001) set the criterion for the neurofeedback as ±0.85 standard deviation of the rolling average of alpha asymmetry across neurofeedback blocks (Allen et al., 2001). Peeters and colleagues (2014) and Quaedflieg and colleagues (2016) used alpha asymmetry measured at baseline. Although the efficacy of the neurofeedback intervention was confirmed across the protocols, no previous investigation has directly tested the effect and efficacy of one protocol over others. Our results indicated that the criterion for the neurofeedback intervention should aim to increase/decrease alpha power in each site by at least 3% from baseline values to induce distinct frontal asymmetry patterns in cortical activity. Lastly, we demonstrated that although small, the effect of the intervention was specific to the trained location (alpha power F4 and alpha power F3) with no effect on alpha asymmetry at Fp1 and Fp2. This finding confirmed the results reported by Quaedflieg et al. (2016) who found a specific effect of the neurofeedback training in the sites (F3 and F4) used to provide the feedback signal.

### ***Effect of Neurofeedback on Time-to-Exhaustion Variables***

The present investigation integrated a broad psychological and physiological assessment which allowed examining the mechanisms underpinning the expected beneficial effect of neurofeedback intervention on performance. In particular, it was hypothesised that neurofeedback to increase relative left frontal cortical activity would influence attentional focus by redirecting the attention toward performance-related cues. Attentional focus therefore was assessed using three main categories, active self-regulation, internal sensory monitoring and distraction derived from the working model by Brick et al. (2014). Consistently with the performance finding, attentional focus ratings were not significantly affected by the neurofeedback intervention. When looking at the frequencies of specific thoughts within each category, in both conditions participants mostly focused on controlling cycling cadence, cycling technique and self-talk while fewer participants adopted cognitive (e.g., chunking) or relaxing strategies. In line with this, Brick et al. (2016) reported that during externally controlled exercise, as were the TTE tests of the current study, individuals tended to focus more on cadence and technique. In addition, in both conditions participants largely monitored internal sensations like muscle pain and body discomfort and these thoughts could be inefficient for cycling performance (see for example Whitehead et al., 2018). Contrary to our hypothesis the increase left-side cortical activity neurofeedback did not dampen negative thoughts or benefit goal-orientated thoughts compared to the opposite neurofeedback. On the basis of this result, one could argue that the alpha asymmetry neurofeedback acted on specific cognitive functions (see for example Harmon-Jones, & Gable, 2009) that however may not be reflected in self-reported cognitive style, at least not in the categories of the present questionnaire.  However, it is also likely that the small effect of the neurofeedback on cortical activity did not last enough to influence TTE performance and cognition during the tests.

Allen et al. (2001) showed that EEG-neurofeedback for frontal alpha asymmetry altered affective state. Specifically, they found that neurofeedback to increase left cortical activity leads to a significantly more positive affective state and induced facial EMG activity associated with happy face in response to emotion-eliciting movie. However, unprovoked affective state (i.e., resting measure of the PANAS) was not affected by the neurofeedback, suggesting that alpha asymmetry is relevant for behaviour in emotion-eliciting contexts. Built on this, affective responses to the cycling TTE test were measured with the feeling scale (Hardy & Rejeski, 1989). It was expected that the neurofeedback to increase relative left cortical activity would lead to a slower decline of positive affect (decreased/increased ratings of pleasure/displeasure) and, consequently, longer performance. Accordingly, Hertman et al. (2019) showed that a glycogen depleting protocol reduced cycling time-to-exhaustion and this performance reduction corresponded to a steeper decline of positive affect during the test. Importantly, the rate of decline in the time-to-exhaustion performance and positive affect correlated (Hertman et al., 2019). On the other side, Elliot et al. (2005) reported that motivational music enhanced positive affective responses during a cycling test compared to non-music condition and allowed participants to sustain greater work by covering longer cycling distance although they also reported greater perceived effort. In the present study, as exercise became more effortful, feelings declined significantly reaching on average about -2.5 (*bad*). This affective state was reflected in the high number of thoughts related to muscle pain and body discomfort. Although FS ratings in NFL tended to be more positive compared to those in NFR, this difference was not statistically significant. It is possible again that the small effect of the neurofeedback on cortical activity did not last enough to influence feelings elicited with TTE tests.

### Limitations and Future Direction

Because the neurofeedback interventions did not produce a strong asymmetry pattern in frontal cortical activity, we could not draw firm conclusions on the use of the neurofeedback intervention to modify frontal alpha asymmetry to overcome the detrimental effect of mental fatigue on performance. Hence, we encourage future study to directly test the hypothesis that neurofeedback training reverses the effect of mental fatigue by adopting a 2 neurofeedback - control × 2 mental fatigue-control design.

Our results showed that the increase right cortical activity neurofeedback was not as effective as previously reported. Because subjective experience of the intervention has been shown to influence the efficacy of the neurofeedback (Alkoby et al., 2018), future investigations should gather information on the participants' experience and test whether they moderate the behavioural outcome following the interventions. Moreover, as mentioned above, the neurofeedback intervention was more effective when a higher threshold was used as criterion (e.g., 3%) compared to the lower threshold (e.g., 1.5%) and the increase alpha asymmetry pattern (NFL) was easier to reproduce compared to the decrease alpha asymmetry

(NFR). In a similar vein, individual differences in neurophysiological activity (e.g., baseline alpha band power) could account for the learning ability during the neurofeedback intervention (see for example Wan et al., 2014). Hence, in general, more investigations are required to refine the neurofeedback protocol that best establishes a clear asymmetry pattern of frontal EEG activity. These investigations may also include neurophysiological predictors of neurofeedback intervention learning ability. Lastly, although our sample size met the requirement of the power analysis, it was still smaller than that used by Mottola et al. (2020) and could have been relatively small to detect the expected results of some variables assessed. Hence, it could be beneficial for future investigation to replicate the experiment with larger sample.

## Conclusion

The present experiment investigated the mechanisms of neurofeedback to modify asymmetric frontal activity for endurance performance after a mentally fatiguing task. Because the results did not show a clear benefit for the performance, more research is required to establish the neurofeedback protocol to modify frontal alpha asymmetry and directly investigate the hypothesis that increased left-sided frontal cortical activity is beneficial for endurance performance after a mentally fatiguing task.

# CHAPTER 6

## GENERAL DISCUSSION

This thesis focused on cognitive challenges and their effect on post-exercise recovery and performance. More specifically, the first two experimental chapters focused on the interplay between mental fatigue and post-exercise recovery. These chapters investigated the effect of mental fatigue on post-exercise recovery by using an empirical approach in a laboratory setting and then an observational design in a field setting. Whereas the latter two experimental chapters examined the effect of EEG-neurofeedback interventions to modify frontal hemispheric asymmetry on endurance performance after a cognitively demanding task. This final chapter summarizes the main findings of each chapter dividing into their two main research themes. It then integrates the findings and outlines the theoretical implications across these research themes. Lastly, this chapter covers some limitations that have not been acknowledged within the experimental chapters yet and provides further suggestions for future research.

Chapter 2 investigated the effect of mental fatigue on post-exercise recovery with a multidisciplinary approach in a laboratory setting. Results of this chapter did not provide evidence of a detrimental effect of mental fatigue on post-exercise recovery. Building on the findings in Chapter 2, Chapter 3 adopted an observational approach to investigate the relationship between mental fatigue and post-training recovery and address this topic in an applied and chronic setting. This time self-reported mental fatigue was negatively associated with self-reported post-exercise recovery.

Lastly, Chapters 4 and 5 investigated the effect of the EEG-neurofeedback to modify frontal hemispheric asymmetry received after a cognitively demanding task on the following whole-body endurance exercise performance. The results from Chapter 4 provided consistent evidence that increasing relative left frontal cortical activity via EEG-neurofeedback had a beneficial effect on endurance exercise performance. Built on these results Chapter 5 implemented the same neurofeedback intervention and investigated the mechanisms underpinning the effect of EEG-neurofeedback to modify frontal cortical asymmetry on whole-body endurance performance following the same cognitively demanding task. Continuing with the interdisciplinary approach used in Chapter 2, physiological and psychological makers associated with mental fatigue and frontal hemispheric activity were assessed throughout the session. However, this time the neurofeedback intervention did not improve the endurance performance test significantly. A comparison between the two studies is provided in paragraph *EEG-Neurofeedback and Frontal Hemispheric Asymmetry*.

## Cognitive Challenges and Post-Exercise Recovery

Chapters 2 and 3 focused on mental fatigue and post-exercise recovery. Because fatigue induced with physical and mental effort share some psychological (e.g., mood disturbances; see for example Kenttä et al., 2006; ten Haaf et al., 2017; Marcora et al., 2009) and physiological (parasympathetic suppression; see for example Stanely et al., 2012; Melo et al., 2017) symptoms, it was hypothesised that mental fatigue would increase the burden imposed by prior exercise to some body systems, ultimately impairing post-exercise recovery from endurance exercise. Results from Chapter 2 showed that mental fatigue does not impair *acute* (90 min) post-exercise recovery, however Chapter 3 showed that in *long-term* recovery (over 24 hr) mental fatigue could reduce perception of recovery state and impair morning mood state.

The experiment reported in Chapter 2 sought to fill an important gap in the literature by identifying what happens to markers of acute recovery when a mentally fatiguing task takes place immediately after the completion of demanding physical exercise. This was tested via a multidisciplinary approach integrating physiological, psychological and neural markers of recovery and fatigue. Participants completed three separate experimental visits where they underwent 45-min intense endurance exercise immediately followed by either a 40-min sustained cognitive task or a 40-min documentary watching (control condition). In the last control condition completed the 40-min cognitive task without prior intense exercise. At the end of each visit a cycling time-to-exhaustion test was conducted to compare the effect of the manipulations on participants ability to perform. This paradigm, whereby a sustained cognitive activity (standardized cognitive tasks longer than 30 min, see Van Cutsem et al., 2017) is performed prior to an endurance test, was firstly introduced in sport science literature by Marcora et al. (2009) and then replicated by several investigations (e.g., Brownsberger et al., 2013; MacMahon et al., 2014; Martin et al., 2016; Pageaux et al., 2014). In these investigations, the effect of mental fatigue on performance is compared against a control condition where participants performed a non-demanding activity (such as watching a neutral documentary).

In line with these investigations (e.g., Martin et al., 2016; Pageaux et al., 2014), the results of rating scale of mental effort and the NASA Task Load Index indicated that the 40-min post-exercise cognitive task was highly demanding, and most importantly it elicited greater mental effort compared to the control task (40-min documentary). Other markers of mental fatigue (e.g., theta and alpha power from the EEG signal, vigour and fatigue from the BRUMS) confirmed that this manipulation, both alone and followed by the 45-min cycling exercise, induced a state of mental fatigue. Nonetheless, contrary to the main hypothesis post-exercise recovery markers and the subsequent time-to-exhaustion test performance were not differently affected by the mental fatigue manipulation when compared to the control condition. Hence, the findings provide little support for the detrimental effect of mental fatigue on acute post-exercise recovery. However, it was conceded that this may be due to the effect that acute endurance exercise had on some of the markers. Indeed, on the one hand physical exercise exacerbated the subjective feeling of fatigue, induced a threat-like state and decreased perception of recovery. On the other hand, it had a small beneficial effect on cognitive performance (this is discussed further in the next paragraphs).

Built on this inconsistency, Chapter 3 adopted an observational approach whereby the effect of mental fatigue on post-exercise recovery was examined in an ecologically valid setting and simultaneously over a more chronic period to overcome the acute effect of exercise. In this chapter, mental fatigue was captured with self-reported measure of mental fatigue experienced throughout individuals' daily routine, while physical exercise was based on training load. By using a multilevel approach, it was possible to exclude intraindividual variability from the first level of analysis so that the relationship between mental fatigue and post-exercise recovery was tested on a daily basis for each individual.  Adding to the findings of Chapter 2 results from Chapter 3 showed that at the daily level of analysis, mental fatigue was negatively related to self-reported post-exercise perceived recovery state, even when training load and muscle soreness were added as predictors to the analysis. This suggested that mental fatigue can undermine the experience of recovery from the exercise session. Interestingly, previous studies have shown that perception of recovery is associated with parasympathetic reactivation (i.e., greater perceived recovery after exercise is positively correlated with greater HRV) (see for example, Stanley et al., 2012).

Hence, short-term acute recovery is not influenced by mental fatigue, whereas mental fatigue cumulated throughout the day is negatively associated with self-reported perceived recovery state after training. Although, the studies in this thesis could not provide a conclusive answer to whether mental fatigue affects post-exercise recovery, they do have some theoretical and methodological implications that are discussed below (See *Mental Fatigue and Physical Fatigue, Mental Fatigue and Performance)*.

## Cognitive Challenges, EEG-Neurofeedback and Endurance Performance

Continuing with the interdisciplinary approach adopted in Chapter 2, Chapter 4 and 5 investigated whether the EEG-neurofeedback to modify frontal hemispheric asymmetry received after a cognitively demanding task would improve the following endurance. EEG-neurofeedback represents a novel yet unexplored intervention in the field of endurance performance. This psychophysiological intervention represents an applied tool to improve endurance exercise performance and, at the same time, offers an experimental method to investigate the causal role of specific brain oscillation for cognition and behaviour. The neurofeedback intervention was built on the approach-withdrawal model of frontal hemispheric asymmetry (Davidson, 1992; Davidson, 2004; Harmon-Jones et al., 2018; Reznik & Allen, 2018). It was hypothesized that the increased relative left frontal cortical activity neurofeedback after a cognitively demanding task would improve endurance performance. Because prior cognitively demanding activities are known to increase perception of effort during the exercise (Van Cutsem, Marcora et al., 2017), it was also hypothesised that the neurofeedback intervention should be accompanied by a reduction of perceived effort during the endurance exercise task. Chapter 4 confirmed the first hypothesis in a two-part experiment. Experiment 1A adopted a between-subject design and showed that participants who received the increased relative left frontal cortical activity intervention were able to cycle for approximately six minutes (about 30%) longer than participants who received either an opposite intervention (increased relative right frontal cortical activity) or the passive control group who received no neurofeedback intervention. Experiment 1B used a within-subject design with the same individuals who participated in 1A. This time individuals received one of the two neurofeedback interventions on separate occasions. In this instance, participants cycled for approximately two minutes (11%) longer in the increased left condition compared to the increased right condition. Changes in the behavioural outcome were accompanied in both experiments by significant changes in the frontal hemispheric asymmetry. These experiments provided promising findings, however, the mechanisms behind the effect of the neurophysiological changes induced with the neurofeedback interventions on exercise performance remained speculative. With the aim to elucidate such mechanisms, Chapter 5 replicated the neurofeedback interventions in a within-subject design and assessed further variables associated with frontal hemispheric asymmetry and relevant for endurance performance. In this chapter, the assessment included baseline affective state as well as affective state elicited during the cycling time-to-exhaustion test as predicted by the valence (Heller, 1993) and capability model (Coan et al., 2006) of frontal hemispheric asymmetry. Based on the evidence around cognitive scope and frontal hemispheric activity (e.g., Harmon-Jones & Gable, 2009), Chapter 5 also introduced the assessment of attentional focus to determine whether the neurofeedback may affect attentional processes during the performance. Lastly, Chapter 5 included measures of mental fatigue prior to and after the cognitively demanding task (e.g., self-reported mental fatigue, frontal alpha and theta power form the EEG signal). These measures confirmed that the writing task adopted induced a state of mental fatigue. However, performance results from Chapter 5 were not consistent with those reported in Chapter 4. This time, no difference in performance was found between the two neurofeedback conditions. Because the effect of the intervention on the frontal alpha asymmetry was smaller compared to that reported in chapter three and other previous studies (e.g., Mennella et al., 2017; Peeters et al., 2014), it has been argued that the effect of the neurofeedback on this sample may not be strong enough to elicit a behavioural effect. The study did not provide support for the effect of neurofeedback on affective state measured during the exercise or at baseline. Likewise, the neurofeedback did not affect significantly self-reported attentional focus during the exercise.

Altogether results from Chapters 4 and 5 are somewhat contradictory and leave scope for more research before drawing firm conclusions about the effect of EEG-neurofeedback to modify frontal hemispheric asymmetry on endurance performance in a mentally fatigued state. The theoretical and methodological implications are discussed below and integrated with findings of Chapter 2 and 3.

## Mental Fatigue and Exercise Induced Fatigue

Physically induced fatigue has usually referred to peripheral and local processes that result from sustained physical exercise, such as muscle glycogen depletion, and accumulation of metabolites (e.g., hydrogen ions, inorganic phosphate), (see Ament & Verkerke 2009). Over recent decades however central fatigue and in particular the psychology of fatigue has become a central topic in research on endurance performance (Pattyn et al., 2018). Indeed, over the last two years, four meta-analyses have been published about the effect of mental fatigue / self-control on sport performance (i.e., Brown et al., 2020; Giboin & Wolff, 2019; Holgado et al., 2020; McMorris et al., 2018). The reported negative effect of mental fatigue on performance ranges from small (McMorris et al., 2018) to medium (Brown et al., 2020), though see Holgado et al. (2020) for opposite findings. Moreover, rating of perceived effort has been the most studied variable that mediates the effect of mental fatigue on endurance performance (see Van Cutsem, Marcora et al., 2017). Accordingly, it has been extensively reported that the performance of cognitively demanding tasks prior to an endurance exercise exacerbates rating of perceived effort across different type of exercise (e.g., Marcora et al., 2009; Smith et al., 2015) in accordance with the psychobiological model of endurance performance (Marcora, 2008; Marcora & Staiano, 2010). This model, based on the motivational intensity theory (Brehm, 1989), predicts that exercise termination occurs when the effort required to sustain the exercise reaches the maximal effort the individual is willing to exert to succeed in the task (potential motivation); or when the individual believes that continuation is impossible (Marcora, 2008). Hence, when athletes are mentally fatigued, they experience higher level effort during the exercise and ultimately, they reach earlier the maximal level of effort they are willing to exert compared to when they are rested. Despite this growing interest into the topic of mental fatigue and endurance performance, the underlying neurophysiological mechanisms of the carry-over effect of mental fatigue on perceived effort remained speculative and few researchers adopted a multidisciplinary psychophysiological approach to investigate such mechanisms (see, for example, Van Cutsem, De Pauw et al., 2017).

In Chapter 2, a multidisciplinary approach was adopted to provide a comprehensive understanding of the interplay between fatigue induced with physical and mental effort, which was at the basis of the hypothesised negative effect of mental fatigue on post-exercise recovery. In particular, results from Chapter 2 highlighted some markers that may be common to fatigue as induced with mental and physical effort. In the chapter, the analysis of the EEG signal showed that theta power increased significantly throughout the 90-min recovery period across frontal and occipital sites. Increased theta power across the scalp has been indicated as a possible marker of mental fatigue (e.g., Wascher et al., 2014). Accordingly, several investigations have reported increasing theta power in tandem with time-on-cognitive tasks across the scalp (Boksem et al., 2005; Craig et al., 2012; Wascher et al., 2014) or at frontal sites (Trejo et al., 2015) as well as at end of prolonged cognitive tasks (e.g., Barwick et al., 2012). Similarly, in Chapter 2, alpha power was found to increase significantly after the cognitive tasks consistently with previous research assessing time-on-cognitive task effects (e.g., Boksem, et al., 2005, Barwick et al., 2012). From one side, the results presented in Chapter 2 replicated these previous and robust findings of the literature. However, this increment was not specific for the mental fatigue conditions. Instead, frontal theta and alpha power increased significantly and similarly across conditions throughout the visits.  Hence, Chapter 2 also expanded previous research by indicating that this neurophysiological feature may not be specific for mental fatigue.

Along with this reduced cortical activation, at the end of the 90-min recovery period in every condition vigour and positive affective state declined, while subjective feelings of fatigue increased. Moreover, Flanker task response time increased significantly over time, although this increase was stronger in the cognitive task conditions (with and without prior exercise) compared to the exercise and documentary condition. In line with these findings, Moore et al. (2012) reported an increased response time during a visual discrimination task along with reduced self-reported mental energy at the end of 65 min recovery period following a strenuous exercise. However, few other studies have investigated the effect of exercise on these variables after more than 30 min from the exercise.

Altogether the results may indicate that increased theta power over the scalp represents a neurophysiological feature of subjective fatigue independently of its source, i.e., sustained exercise sustained cognitive activities or attention and reflects dampened cortical activation and cognitive processing. This perspective is consistent with the stream of research on vigilance and sleep deprivation. Accordingly, studies on the neurophysiological characteristics of vigilance decrements and sleep deprivation reported that theta power increased during period of sustained attention in a vigilance task (Paus et al., 1997) and wakefulness (Cajochen et al., 1995). On a similar line, it has been proposed that increased power in the lower-alpha frequency band at frontal sites throughout periods of wakefulness signals the increasing effort to maintain the attention on the task at hand (Klimesch, 1999). In line with this, it has been proposed that declines in performance derived from time-on-task and sleep deprivation share similar underlying neurophysiological mechanisms (Gunzelmann et al., 2010).

Chapter 3 expanded further these findings showing that mental fatigue and training load negatively predicted morning self-reported energy while controlling for sleep quality. This indicates that greater experience of mental fatigue contributes in tandem with greater subjective exercise workload to reduced morning energy and increased morning fatigue even if the individual had a good night sleep. Chapter 2 and 3 results would suggest that while acute exercise may have a temporary and mild beneficial effect on cognition (discussed in more details below, *The Acute and Long-Term Effect of Exercise: Fatigue or Arousal*), self-reported symptoms of fatigue induced with exercise could manifest later in time and mental fatigue accumulate throughout the day could exacerbate this manifestation. These results are in line with the findings by Stults-Kolehmainen and Bartholomew (2012) and Stults-Kolehmainen, Bartholomew and Sinha (2014). The first study reported no relationship between chronic psychological stress and self-reported measures of recovery within 60 min following a resistance exercise. On the contrary, the second study found that chronic psychological stress moderated the recovery trajectories of self-reported physical energy, physical fatigue and muscle soreness measured throughout the 96 hr after the same resistance exercise protocol. Interestingly, this delayed manifestation of subjective fatigue symptoms was also reported in studies on mental fatigue (Schellekens et al. 2000). In this last study, participants engaged in 8 hr of simulated workday. Self-reported, behavioural and physiological variables of mental fatigue were measured at the beginning (09:00 am), at the end (05:00 pm) of the simulated-working period and after 2 hr (7:30 pm) from the end. Their results showed that in the first post workday assessment (05:00 pm) participants accuracy in the probe memory-search task decreased significantly compared to the control condition (low-demanding simulated workday). However, only in the latest assessment this decrement was accompanied by significantly greater self-reported deactivation (lower energy) and fatigue. Results from Chapter 3 would expand this suggesting that the effect of mental fatigue, accumulated over the day, on self-reported energy and fatigue could persist after a night of sleep. Overall, it seems that it is necessary to capture behavioural and subjective measures over time to gain insight into the subjective experience of fatigue.

Taken together the results from the observational and empirical study suggested that fatigue from physical and mental effort could be equally experienced at least at the subjective and cortical levels. These results fitted with the hypothesis that a common network is used to evaluate physical and mental effort and determine whether an activity should be pursued (Boksem & Tops, 2008). In this framework, subjective feeling of fatigue manifests from a cost-benefit analysis (or opportunity-cost estimation) when the cost outweighs the benefit derived from the activity (see Boksem & Tops, 2008; Inzlicht & Schmeichel, 2012; Kurzban et al., 2013). Although the models proposed by these authors have some theoretical difference, the fundamental concept of these models is that fatigue arises from sustained/sequential effort to discourage the organism from pursuing inefficient and highly costly behaviours. This theoretical framework seems to explain the commonalities between the experience of fatigue from sustained mental and physical effort, the carryover effect of mental effort to exercise performance and task disengagement during sustained (cognitive /physical) performance. Among the key brain structures involved in this cost-benefit processes, several authors (Boksem & Tops, 2008; Kurzban et al., 2013; Hockey, 2013) have highlighted the bidirectional dopaminergic pathway between the prefrontal areas (orbitofrontal cortex) and the striatum in the basal-ganglia that plays a central role in reward processing and initiation/continuation of effortful (physical and mental) behaviour (response vigour, e.g., Zenon et al., 2016). The anterior cingulate cortex, ACC, is involved in effort-based decision making by signalling effort trade-off, namely whether to pursue or not an action (Vassena et al., 2017). Boksem and Tops (2008) also suggested that the insula, thanks to the connection with autonomic and visceral centres, is implicated in monitoring the peripheral resources and hence in processing the energetic cost of an action. Several other networks could be involved in the experience of fatigue and the neuromodulations among these networks could accommodate behavioural and affective influences of fatigue (see Pattyn et al., 2018 for a discussion on this topic).

In accordance with the motivational account of mental fatigue, results from Chapter 2 showed that the physical task (alone and followed by the cognitive task), as well as the cognitive task alone, resulted in reduced motivation for the following exercise. In Chapter 2, participants also reported to be less able to cope with the demand of the cycling time-to-exhaustion test after the 45-min cycling task compared to baseline, resource-demand evaluation also declined after the cognitive task alone condition. However, in this last condition, the reduction in the resource-demand evaluation and motivation was smaller and limited in time. Recently it has been suggested that this threat state resulting in blunted-cardiovascular reactivity to external challenges could reflect motivational disengagement (see Hase et al., 2020). Thereby, this negative resource-demand evaluation of the cycling time-to-exhaustion task may subserve motivational disengagement from inefficient behaviour when the organism has not (perceived) energy to cope with it (McEwen & Gianaros, 2011; Touroutoglou et al., 2019). Lastly, results of Chapter 4 suggests that the neural systems underlying approach motivation may compensate the detrimental effect of cognitively demanding tasks on endurance performance although further research is needed to corroborate the findings.

## Cognitive Challenges and Endurance Performance

The variability in the reported negative effects of mental fatigue on endurance performance (e.g., Brown et al., 2020; Giboin & Wolff, 2019; Holgado et al., 2020; McMorris et al., 2018) suggests that, although mental fatigue could influence endurance performance, this effect may not generalize across contexts and athletes (e.g., Martin et al., 2016; Van Cutsem, De Pauw et al., 2017). For example, Chapter 2 of this thesis showed that mental fatigue induced after demanding physical exercise did not affect subsequent endurance performance in a further bout of exhaustive exercise performed soon afterwards. Likewise, Van Cutsem, De Pauw et al. (2017) showed that mental fatigue did not impair performance in the heat. Interestingly the authors suggest that when perception of effort is already exacerbated by other environmental factors, there is a sort of floor effect that prevent further disruption of performance. That is, the effects of different stressors may not summate to increase the rating of perceived effort during the exercise.

In light of what has been reported in the previous paragraph, it could be speculated that stressors that are more challenging for the organism (e.g., thermoregulation, energy availability) are prioritized in the computation of perceived effort during the exercise and may obscure the effects of mental fatigue. Yet, it remains to be established whether this proposed floor effect that occurs when different stressor summate on exercise performance depends on the nature of the computerised cognitive tasks that are used in experimental research. Indeed, these mental tasks may not require as much as effort as “real-world” activities and hence their effect on performance may be limited when others, more challenging events, occur. On the other hand, everyday tasks usually involve emotional components and may require greater effort, hence their effect on the autonomic system, self-reported measures and exercise performance could be far greater to that found in Chapter 2. Relevant to this, Chapter 3 implemented the first attempt to translate the experimental findings on mental fatigue from laboratory-computerized task to “real-world” activities. However, this Chapter did not include the assessment of performance. Hence, this approach may be used to examine when and where mental fatigue influence endurance exercise performance.

Chapters 4 and 5 investigated cognitive challenges and endurance exercise performance from a different perspective. In both studies, the effect of neurofeedback intervention to modify frontal hemispheric asymmetry on endurance performance was tested after a cognitively demanding task. Although the tasks used in Chapters 4 and 5 were built on the “ego-depletion” literature, this cognitive task resulted in reduced self-reported vigour and self-control (Chapter 4) and increased mental fatigue and theta power (Chapter 5), consistently with the results from the laboratory study of Chapter 2. Hence, this suggests that individuals in Chapter 5 underwent the neurofeedback interventions in a mentally fatigued state. These results are in line with the interpretation of cognitive self-control as a form of short-term mental fatigue and are corroborated by the recent meta-analysis by Brown et al. (2020). The authors showed that the length of the cognitive task (> 30 min or < 30 min) did not influence differently the size of the negative effect of the cognitively demanding task on endurance exercise performance.

Altogether this further supports that subjective and behavioural symptoms of cognitive self-control exertion match those of acute mental fatigue.

Although results reported in Chapters 4 and 5 requires further examinations, Chapter 4 suggested that hemispheric frontal asymmetry may improve endurance performance in the face of mental fatigue. Results showed that this effect was not mediated by rating of perceived effort. Likewise, mood state (subjective feeling of fatigue and vigour) did not mediate this effect, indeed fatigue and vigour dimensions of mood did not recover to baseline after the neurofeedback to increase relative left frontal hemispheric asymmetry. On the contrary, results of Chapter 4 would suggest that frontal hemispheric asymmetry interacts with mental fatigue at a different level. For example, it could be argued that left-sided asymmetry increased importance of success or perception of coping resources counteracting the negative effect induced by mental fatigue on these same measures (see Chapter 2 results). This would explain why participants did not report a lower perception of effort during the exercise, even though they were able to cycle for longer. However, in light of the inconsistencies between results of Chapter 4 and Chapter 5, it is not possible to draw strong conclusions about this effect and further research should be done on this topic as suggested below (*EEG-Neurofeedback and Frontal Hemispheric Asymmetry*).

## The Acute and Long-Term Effect of Exercise: Fatigue or Arousal

Despite the commonalities between fatigue arising from physical and mental effort, endurance exercise had effects that are in contrast with those elicits with prolonged cognitive tasks.  In particular results of Chapter 2 and 3 showed that although mental effort and physical effort could induce a similar experience of fatigue over a more prolonged period (> 1 hour), the intense cycling exercise used in Chapter 2 may have triggered an acute sympathoexcitatory response that was accompanied by increased cognitive performance (see Basso & Suzuki, 2017 for a review on this topic). This sympathoexcitatory response, indicated by parasympathetic suppression in the two conditions that involved a prior 45-min cycling task, was partly reflected in self-reported vigour and positive affect that remained high in the first assessment right after the exercise. However, it was not reflected in any neurophysiological features or other psychological variables. Moreover, Chapter 3 found a positive, though non-significant, relationship between training load and morning self-reported energy at the individual level of analysis (between-subject). The great intraindividual variability in the response to exercise indicates that several intrapersonal factors could moderate the relationship between exercise and mood state such as age, self-reported psychological stress (see for example, Stults-Kolehmainen et al., 2016) but also the environmental influences and exercise regimen (e.g., Berger & Motl, 2000). Overall, these findings have two main implications. Firstly, the sympathoexcitatory effect of acute endurance exercise could result in blunted cardiovascular reactivity to the following stressors (cognitive task) (e.g., Brownley et al., 2003; see also Hamer et al., 2006 for a review). This would explain the lack of effect of the cognitive task that followed the exercise on HRV. However, the greater self-reported threat-like state found in the acute exercise conditions compared to baseline suggested that this blunted cardiovascular reactivity may be driven also by central factors as previously suggested. Secondly, this sympathoexcitatory effect was accompanied by a beneficial effect on cognitive performance during the 40 min cognitive task manipulation. Precisely, in the condition with the prior 45-min cycling task individuals reported higher accuracy in the incongruent trials of the Stroop task, indicating that the endurance exercise may have facilitated the Stroop performance. Although this was a rather small facilitative effect, the cognitive task was performed continuously for 40 min, and the learning effect, which occurred in the condition with no prior exercise, backed the differences. Moreover, Flanker task response time in the condition exercise + documentary was less affected over time compared to both conditions with the 40-

min cognitive task. Hence, acute exercise may have a facilitating effect on cognition and partly counteract the symptoms of mental fatigue on cognitive performance.

The effect of acute exercise on cognition has been broadly studied. However, investigations on this topic have mainly used short tasks (< 10 min) to assess cognitive performance as such the effect of exercise on sustained cognitive performance had not been fully investigated yet. Moreover, even though different meta-analyses found a small positive effect of acute exercise on cognitive functions (Chang et al., 2012; Lambourne & Tomporowski, 2010; Ludyga et al., 2016; McMorris, & Hale 2012), results from singular investigations were highly heterogeneous and several variables were shown to moderate the relationship. For instance, exercise intensity is one of the primary factors moderating the outcome (Chang et al., 2012). The majority of the studies pointed to the Yerkes and Dadson law of the inverted-U relationship between arousal and performance according to which moderate intensity, but not high, or low intensity should enhance cognitive performance. However, the exercise characteristics have never been standardized and varied among the studies, so it remained unclear which exact exercise intensity and duration could be preferable. Besides, other moderators could simultaneously affect the relationship between exercise and cognition, for example, individuals' fitness level and experience (Chang et al., 2012), the type of the cognitive task assessed (e.g., Chang et al., 2012; McMorris, & Hale 2012), participants' age (Ludyga et al., 2016). Because all these factors were heterogeneous across the different investigations, the prediction based on the inverted-U shape is still controversial (Chang et al., 2012).

The greater inter- and intra-individual variabilities found in cognitive performance (response time and accuracy) in Chapter 2 confirmed that the effect of exercise on cognition is highly dependent on the context and the individual. Moreover, the effects reported on cognitive performance receded by the end of the 40-min cognitive task. Hence, although exercise may have an acute and beneficial effect on cognitive performance when the cognitive task extends over time fatigue could overcome this cognitive enhancement.

The effect of acute exercise on cognition could be interpreted in term of the brain adaptations that occurred during and after the exposure to external stressors. Accordingly, exposure to moderate stressors is characterized by an acute enhanced activation and arousal which serves to evaluate the situation and mobilize the energetic resources (de Kloet et al., 2005). This activation is followed by a period of adaptive memory consolidation to prepare for future events (de Kloet et al., 2005). The complex interactions of the neurotransmitters that guide the stress-response and timing of action could explain the controversial relationship between exercise and cognitive performance as well as the different moderators, such as the type of cognitive tasks, the delay from exercise, and the exercise characteristics. For instance, the synaptic effect of neuropeptides and monoamines, like norepinephrine and corticotrophin-releasing hormone, takes place in a short time by increasing the membrane excitability within the brain area in which they are released; their action mediates the acute increase in arousal, vigilance and alertness (de Kloet, et al, 2005). Nevertheless, they could also exert a long-lasting genomic effect that generates a cascade of molecular changes mediated by transcriptional regulation (Joëls, & Baram, 2009). Glucocorticoids, likewise, can target the cell membrane exerting a fast action, at the same time they can have a delay and long-lasting effects through mineralocorticoid and glucocorticoid receptors that mediate gene transcription (de Kloet et al., 2005; Joëls, & Baram, 2009). Hence from one side, neurotransmitters are involved in the onset and maintenance of stress-response, on the other hand they also participate in the recovery of stress response and the consolidation of the situation memory (de Kloet et al., 2005; Ulrich-Lai, & Herman, 2009). Based on this interpretation, the time when the cognitive task is performed is crucial for the outcome, such that during and shortly after the stress-response the organism is focused on coping and encoding the stressor, in this phase perception, attention and encoding are enhanced. In line with that, it was showed by Perini et al. (2016) that acute exercise positively affects the performance of perceptual and motor learning tasks, namely orientation discrimination task and thumb abduction. These brain responses to exercise may also explain the delayed manifestation of subjective feeling of fatigue.

Altogether these results would suggest that future research on the effect of exercise on cognition and affect should incorporate models of stress-response as well as the psychological effect of exercise-induced fatigue. Moreover, beyond the absolute exercise intensity, the subjective experience of fatigue and prolonged assessment of cognitive task should be considered when investigating this topic. These factors could eventually explain some of the inconsistencies. Based on the results highlighted in Chapter 2 and 3 it seems that a longitudinal and within-subject (interindividual analysis) design could be appropriate to advance the understanding of the dynamic between positive and negative effect of endurance exercise on cognition.

## EEG-Neurofeedback and Frontal Hemispheric Asymmetry

Mirifar et al. (2017) highlights the importance for neurofeedback research to use methodologically rigour designs that control for non-training specific variables that could drive the neurofeedback effect. In this perspective, the studies on neurofeedback presented in this thesis, in particular the two-part study in Chapter 4, addressed this issue with a well-controlled design. Accordingly, between groups comparisons in experiment 1A provides important information about the neurofeedback efficacy in term of neurophysiological (e.g., frontal alpha asymmetry) and behavioural outcomes. Individuals of the increased left-asymmetry and increase right groups learnt to modify frontal alpha asymmetry consistently with their training aim. However, the performance benefits were specifically associated with the increased left-asymmetry group. Indeed, no differences have been found between control and increase right frontal asymmetry groups. Importantly, the comparison between the three groups /two conditions rules out any neurofeedback placebo effect. Moreover, the results of experiment 1A Chapter 4 ensured that the positive neurofeedback effect on endurance performance was over and above a period of passive rest. In terms of frontal alpha asymmetry, the control condition/groups accounted for EEG spontaneous changes over time, the simple effect of the sensory feedback and the cognitive effort from engaging in the neurofeedback training.

However, the inconsistencies between the results of Chapter 4 and 5 deserve some methodological considerations that could direct future research on EEG-neurofeedback and frontal hemispheric asymmetry. In these chapters it was found a different effect size of the neurofeedback intervention on frontal hemispheric asymmetry. Chapter 4 in line with previous research reported a medium effect of the 12-min intervention on frontal hemispheric asymmetry (e.g., Peeters et al., 2014). On the other side, Chapter 5 reported a small effect that was highlighted only within the higher threshold protocol (i.e., when frontal alpha power was increased/decreased by 3% relative to baseline measures).

Firstly, even though the two studies implemented the same EEG-neurofeedback protocol, the studies adopted a slightly different approach to determining the baseline level of alpha power used to establish the individual threshold for the neurofeedback training. In Chapter 5, baseline alpha power was measured via five 30 sec recordings in line with the recommendation by Allen et al. (2004). In contrast, Chapter 4 adopted five 10 sec recordings. Because bilateral alpha power decreased significantly from baseline to the neurofeedback blocks in Chapter 5, very short baseline assessment may be more suitable to determine alpha power for individualised neurofeedback threshold. Moreover, it has been suggested that neurophysiological signatures could predict individual response to the neurofeedback training (Alkoby et al., 2018; Wan et al., 2014), hence the inclusion of the neurofeedback stimuli during the baseline recording may reduce the variability between baseline assessment and the neurofeedback training. For example, Allen et al. (2001) during the baseline recording of frontal alpha asymmetry asked participants to watch the recording of the neurofeedback to reproduce the same sensory stimuli that would have been found during the intervention.

Once established the appropriate method to define the baseline level of alpha asymmetry, the threshold used to modulate this criterion also required further investigations. In both studies, individuals were asked to modify (increasing or decreasing depending on the sites) their baseline alpha power by 1.5% for the first 3 blocks and 3% in the last three. Results suggested that the 3% threshold may be more appropriate since it led to greater frontal alpha asymmetry score throughout the neurofeedback blocks. An alternative approach consists of adapting the threshold of the neurofeedback based on the previous neurofeedback block. In this way the training is adapted to individual's learning ability (see, Alkoby et al., 2018 for a review on this topic).

As previously highlighted the control conditions/groups are particularly important to link the behavioural outcome to the neurofeedback training. Yet, as evidenced by the divergent results of Chapter 4 and 5, the efficacy of the neurofeedback training on the neurophysiological shift at the individual level could be influenced by other factors that are worth considering.

The effect of neurofeedback training on brain activity depends on unconscious conditioning. Namely, the neurophysiological features that are reinforced are more likely to occur (Cooke et al., 2018; Sitaram et al., 2017). However, during the training, the individuals should effectively use the feedback stimuli to modulate the brain activity and could engage consciously with the learning processes. That is, the performer could use different cognitive strategies and mental states to modulate brain activities (see, for example, Davelaar, 2018). Such cognitive strategies may include focusing the attention inward or outward, using specific thoughts, relaxation techniques and so on. To add complexity, these attentional processes could be influenced by the performer' engagement, mood and motivation during the neurofeedback session and could change within the neurofeedback sessions based on whether the individual feels control over his brain activity and his/her expectation.

Despite neurofeedback have been studied for decades now, little is known about how these factors influence neurofeedback learning mechanisms and affect the neurophysiological changes elicited with the training.  For instance, Hardman et al. (1997) used a frontal hemispheric neurofeedback protocol to modify slow cortical potential toward either right (F4) or left (F3). Moreover, half of the group received specific guidance to aid learning while the other half received general information about neurofeedback. They reported that both groups learnt to modulate the slow cortical potentials. However, the no-guidance group showed greater variability throughout the training. Namely, individuals with no strategic guidance tended to perform poorly at the beginning of the training yet had stronger differentiation among the neurofeedback conditions by the end of the training. Hence, external guidance could aid the learning at the start while impeding learning advancement later.

In the studies presented in Chapters 4 and 5, the individuals were instructed to sit quietly and maintain their focus on the feedback stimuli. Moreover, they were told that during the training they could adopt any strategy that helps them to modulate the cortical activity and there is no wrong-or-right strategy. They were also reassured that it could take some time to learn to effectively modulate their brain activity. Thereafter, participants did not receive other instruction and feedback from the researcher. This was done to standardise the neurofeedback instruction among individuals and conditions. Yet, it is plausible that the interaction between the researcher and the participant could promote individuals' engagement, compliance, and motivation throughout the neurofeedback training (see Glannon, 2014).

To advance the understanding of this topic, future research on neurofeedback training could benefit from including information about performer experience and strategies during the training. For example, a semi-structured interview could be implemented at the end or between neurofeedback blocks to gain insight into what participants think, feel and do during the training. Moreover, different instruction protocol could be compared.

This information could be particularly relevant from an applied perspective if one wants to teach the athletes to reproduce the target brain activity in the absence of contingent feedback (e.g., Ring et al., 2015). Additionally, from a theoretical standpoint, this information could help disentangle training specific effect from non-specific effect. That is, what strategies individuals become aware of /and learn because of the contingent feedback and what mental states could be elicited with the training independently from feedback yet interact with the training at the behavioural and neurophysiological level.

Lastly, an aspect that requires some considerations is the regional specificity of the neurofeedback training. Quaedflieg et al. (2016) implemented a neurofeedback training to modify frontal alpha asymmetry and found that the effect of the training on alpha asymmetry (F4-F3) spread to adjacent frontal location (F8-F7 and Fc4-Fc3). However, they did not find differences between neurofeedback training groups in the asymmetry score at central (C4-C3) and parietal (P4-P3) sites. Based on their results, one could argue that the neurofeedback training effect is specific for the area trained. However, it is well-known that the EEG signal lacks spatial resolution, and it is unlikely that the origin of the signal is only driven by the active recording site. More importantly, even within the same region, there is a high level of granularity and functional specialization (Mahon & Cantlon, 2011; Miller et al., 2013). Hence, future research should use high density EEG recording to confirm the regional specificity of the neurofeedback training. High density EEG could provide deeper insight into the lateralization patterns that drives the behavioural outcome and advance the understanding of the functional significance of this lateralization. Moreover, comparisons between neurofeedback protocols to modify hemispheric asymmetry across frontal, central, and parietal electrodes could provide additional information related to this issue.

Overall, there is some evidence that individuals can learn to modify their frontal hemispheric asymmetry via frontal alpha asymmetry neurofeedback training. However, the inconsistent findings in the present thesis highlighted that further investigations around the neurofeedback protocol is required to advance our knowledge on the behavioural and affective effects.

## Limitations

The main limitations of the studies have already been highlighted in the discussions of each chapter. However, there are limitations spanning across the experimental chapters that should be addressed. Overall, this thesis provided novel findings by integrating different topics and models in the field of endurance performance, mental fatigue, post-exercise recovery and neurofeedback. The studies of Chapter 2, 4 and 5 adopted repeated measures designs where different measures and tasks were integrated. This approach aimed at providing a thorough understanding of the phenomena studied across conditions and time, it had however two main downsides. First of all, assessing several tasks in sequential order make it more difficult to distinguish the effect generated by each task and ultimately interpret the results. For example, in Chapter 2, the first cycling exercise could have had a partial counter effect to the mental fatigue-inducing manipulation on affective, cognitive and physiological outcomes. Although the length of the task was chosen to minimize this effect (Van Cutsem, Marcora, et al. 2017 suggested task longer than 30 min may be necessary to induce mental fatigue), longer tasks or a long-term assessment that span over more hours may be necessary to disentangle the beneficial effect of exercise on cognition and affect from the opposite effect of mental fatigue. Secondly, the use of sequential tasks leads inevitably to prolonged time in the laboratory. For the study presented in Chapter 2 participants stayed in the laboratory for approximately four hours in each of the three visits. For the studies presented in Chapters 4 and 5 participants spent approximately two hours for each experimental visit. Time spent in the laboratory may influence some psychological variables independently from the manipulations. Indeed, in all experimental studies it was found a linear decline in vigour and increase in subjective fatigue throughout the visits across conditions and group. This "time in the laboratory effect" was equal across groups and conditions, as such, it should have affected the main outcome, i.e., endurance performance, equally. Nonetheless, this "time in the laboratory effect" could have interfered with the treatments, participant compliance with the tasks and the subjective measures as it may induce fatigue (see for example Francis et al., 2018). For this reason, it may be that naturally occurring mental fatigue represents a valuable and more ecological method that future investigations could adopt for studying mental fatigue sport performance context.

Moreover, the multidisciplinary approach adopted in Chapters 2, 4 and 5 represented a challenge in term of study power and sample size determination. By simultaneously assessing physiological, psychological, and behavioural measures, the studies addressed the mechanisms behind the phenomena of interest (e.g., recovery, mental fatigue, approach-avoidance motivation). Nonetheless, the power varies across this wide range of measures and the use of one outcome to determine the sample size could have limited the power of the study to detect a statistically significant effect in the other measures. Specifically, in Chapter 2 a priori-power analysis indicates that the study should be powered enough to detect a medium effect on the behavioural measures. However, this sample size was likely underpowered to detecte the small changes that characterise the self-report measures. Likewise, in Chapter 4 and 5, a priori-power analysis was computed based on the estimated effect of the neurofeedback intervention on alpha asymmetry. Yet, changes in self-report measures may not be detectable with the sample size used. Overall, the results from the self-report data should be interpreted cautiously and future research adopting this multidisciplinary approach should consider integrating the effect sizes from different types of variables when computing a priori power-analysis.

## Future Research and Applied Implications

Firstly, Chapters 2 and 3 left some questions open about mental fatigue and post-exercise recovery. As discussed in the previous paragraph, observational approach represents a viable method to further investigate this topic. In particular, future studies on mental fatigue and post-exercise recovery may adopt an observational multilevel approach whereby naturally occurring mental fatigue (e.g., self-reported mental fatigue) is used as a moderator of post-exercise recovery trajectories of markers assessed after an intense endurance exercise such as EEG signal, heart rate variability and self-reported measures.  Among these markers, research may include hormones, like cortisol and catecholamines which have been associated with both mental (e.g., Schellekens et al., 2001) and physical induced fatigue (e.g., Ronsen et al., 2001). On the basis of the findings presented in this thesis, future investigations should also integrate short- and long-term assessments to disentangle different carry-over effects of exercise on these same markers. For the short-term assessment two hours may be required, for the long-term assessment separate evaluations could be carried out every 24 h (see, for example, Stults-Kolehmainen et al., 2014). In the context of recovery and fatigue, it could be relevant to include central and psychological markers of fatigue induced with intense exercise, such as neurophysiological variables (cortical activity) and cognitive performance. For instance, studies on intensified training routine could integrate these measures.

Within post-exercise recovery literature, the thesis highlighted the lack of research around psychological factors that undermine post-exercise recovery by interfering with exercise-induced fatigue. The present thesis had focused on mental fatigue, nonetheless there may be other external, psychological challenges that could interfere with post-exercise recovery, such as social or emotional challenges. Social isolation for example has been linked to negative affective state and cortisol release (see Blackhart et al., 2007), while difficulties in emotion regulation are associated with decreased heart rate variability (e.g., Di Simplicio et al., 2012). As suggested above, observational approaches could be appropriate as a first examination of these factors on post-exercise recovery. For instance, the relationship between these psychological challenges (e.g., perceived social isolation) and post-exercise recovery markers like cortisol, affective state and heart rate variability may be investigated at first. Latterly, possible manipulations could be implemented after the exercise.

Moreover, observational approaches should also be considered in the context of mental fatigue and endurance performance per se. Although it does not provide a causal account of metal fatigue, it is a first and necessary step to translate mental fatigue findings into an applied and ecologically valid context. Such studies could also test potential moderators, for example personality traits or anxiety and mediators, such as self-efficacy (see for example Graham & Bray, 2015) or affective state. In addition, multilevel approaches would allow tests of the within and between-subject effects and could be used for example to determine the effect of mental fatigue on training routines in endurance athletes.

In the context of mental fatigue, the role of hemispheric frontal asymmetry requires further clarification, in particular future investigations may directly investigate whether approach-orientated processes alleviate the carry-over effect of mental fatigue on exercise performance. Future investigations may examine more in-depth neurofeedback protocols to modify frontal hemispheric asymmetry. Proving the trainability of this neurophysiological feature could pave the way for its application in different performance settings and context. Once a suitable protocol is found, this intervention would constitute a valuable tool to test theoretical models. Future investigations may clarify if left-sided frontal hemispheric asymmetry is associated with improved endurance performance and the cognitive and affective processes that may underlie this effect.

Neurofeedback interventions in general should be examined in the context of endurance performance. For example, Zénon and co-workers (2015) reported that disruption to the supplementary motor area with transcranial magnetic stimulation reduced perception of effort. Hence, it may be that reducing the cortical activity in this area via alpha neurofeedback training could improve endurance performance by reducing perception of effort.

Lastly, from an applied perspective the present thesis offers some evidence-based implications around mental fatigue, performance, and recovery. In particular, the thesis draws attention toward mental recovery. Results of Chapter 2 and 3 suggest that, from a psychological perspective, individuals experience fatigue as a general state independently from its sources, i.e., being it physical or cognitive. Consequently, endurance exercises eventually could lead to mental fatigue. Moreover, the sources of cognitive load throughout daily activities could add to training-related fatigue. In this context, recovery is extremely important to alleviate these symptoms (Kellmann et al., 2018). Coaches are encouraged to consider the different sources of cognitive load when planning athletes training sessions and to monitor athletes' subjective experience of fatigue and recovery. In this regard, self-reported mood state is sensitive to fatigue arising from both mental and physical activities, hence daily mood assessment represents a well-suited and practical monitoring tool for coaches and practitioners. This assessment could be particularly important when working with recreational athletes as well as in situations where cognitively demanding activities alternate continuously with physical activities, e.g., military training.

Furthermore, practitioners working with endurance athletes should consider strategies that foster mental recovery. Neurofeedback technique requires further theoretical and methodological development before taking over in an applied context, nonetheless, there are other strategies already available that could help mental recovery in athletes. Such interventions may include meditation or breathing techniques (e.g., Pelka et al., 2017), autogenic training, nap (e.g., Blanchfield et al., 2018). In addition, further research on these interventions on recovery from endurance exercise and mental fatigue is required to provide further evidence on their effectiveness in an applied setting (see Loch et al., 2019 for a review on this).

## General Conclusions

This thesis focused on the interplay between mental fatigue and post-exercise recovery and mental fatigue and hemispheric frontal asymmetry. In particular, the thesis investigated the effect of mental fatigue on post-exercise recovery by using an empirical approach in a laboratory setting and then an observational design in a field setting. The thesis also examined the effect of EEG-neurofeedback interventions to modify frontal hemispheric asymmetry and endurance performance in the context of mental fatigue.

The main findings of the thesis were as follows: prolonged mentally fatiguing task taking place during the acute post-exercise recovery period does not impair post-exercise recovery markers. However, mental fatigue and training load over 24-h negatively predicted perception of recovery from prior exercise training, and morning self-reported energy and fatigue. EEG-neurofeedback training to modify frontal hemispheric asymmetry may improve endurance exercise following a cognitively demanding task. However, further research around the neurofeedback protocol is required to corroborate the results and further investigate the mechanisms involved.

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# APPENDIX A ETHIC FORMS

## EXAMPLE INFORMED CONSENT

Bangor University

SCHOOL OF SPORT, HEALTH AND EXERCISE SCIENCES

| | | |
|---|---|---|
| 1 | Title of project | |
| 2 | Name and e-mail address(es) of all researcher(s) | Francesca Mottola pep83b@bangor.ac.uk |

Please tick boxes

1 I confirm that I have read and understand the Information Sheet dated …………………. for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2 I confirm that all of the medical information that I have provided on the provided medical history questionnaire is true to the best of my knowledge. ☐

(ii) Students: ☐

I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason. If I do decide to withdraw I understand that it will have no influence on the marks I receive, the outcome of my period of study, or my standing with my supervisor or with other staff members of the School.

(iii) General members of the public: ☐

I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason.

3 I understand that I may register any complaint I might have about this experiment with Professor Tim Woodman, Head of School of Sport, Health and Exercise Sciences, and that I will be offered the opportunity of providing feedback on the experiment using the standard report forms. ☐

4 I agree to take part in the above study. ☐

Name of Participant …………………………………………………………………….

Signature …………………………………. Date …………………………………..

Name of Person taking consent…………………………………………………….

Signature …………………………………. Date …………………………………..

---

WHEN COMPLETED – ONE COPY TO PARTICIPANT, ONE COPY TO RESEARCHER FILE

# EXAMPLE MEDICAL QUESTIONNAIRES

**Informed Medical Consent**

Bangor University

SCHOOL OF SPORT, HEALTH AND EXERCISE SCIENCES

Name of Participant ……..……………………………………………………………..

Age ………………………

Are you in good health? YES ☐ NO ☐

If no, please explain

How would you describe your present level of activity?
*Tick intensity level and indicate approximate duration.*

| | | | | | |
|---|---|---|---|---|---|
| Vigorous | | Moderate | | Low intensity | |

Duration (minutes)…………………………………………………………………….

How often?

| | | | |
|---|---|---|---|
| < Once per month | | 2-3 times per week | |
| Once per month | | 4-5 times per week | |
| Once per week | | > 5 times per week | |

Have you suffered from a serious illness or accident? YES ☐ NO ☐

If yes, please give particulars:

Do you suffer from allergies? YES ☐ NO ☐

If yes, please give particulars:

Do you suffer, or have you ever suffered from:

|  | YES | NO |  | YES | NO |
|---|---|---|---|---|---|
| Asthma |  |  | Epilepsy |  |  |
| Diabetes |  |  | High blood pressure |  |  |
| Bronchitis |  |  |  |  |  |

Are you currently taking medication? YES ☐ NO ☐

If yes, please give particulars:

Are you currently attending your GP for any condition or have you consulted your doctor in the last three months? YES ☐ NO ☐

If yes, please give particulars:

Have you, or are you presently taking part in any other laboratory experiment?

YES ☐ NO ☐

---

PLEASE READ THE FOLLOWING CAREFULLY

Persons will be considered unfit to do the experimental exercise task if they:

- have a fever, cough or cold, or suffer from fainting spells or dizziness;
- have suspended training due to a joint or muscle injury;
- have a known history of medical disorders, i.e. high blood pressure, heart or lung disease;
- have had hyper/hypothermia, heat exhaustion, or any other heat or cold disorder;
- have anaphylactic shock symptoms to needles, probes or other medical-type equipment;
- have chronic or acute symptoms of gastrointestinal bacterial infections (e.g. Dysentery, Salmonella);

- have a history of infectious diseases (e.g. HIV, Hepatitis B); and if appropriate to the study design, have a known history of rectal bleeding, anal fissures, haemorrhoids, or any other condition of the rectum.

PLEASE COMPLETE AND SIGN THE DECLARATION BELOW

**DECLARATION**

I agree that I have none of the above conditions and I hereby volunteer to be a participant in experiments/investigations during the period of …………………20……

My replies to the above questions are correct to the best of my belief and I understand that they will be treated with the strictest confidence. The experimenter has explained to my satisfaction the purpose of the experiment and possible risks involved.

I understand that I may withdraw from the experiment at any time and that I am under no obligation to give reasons for withdrawal or to attend again for experimentation.

Furthermore, if I am a student, I am aware that taking part or not taking part in this experiment, will neither be detrimental to, or further, my position as a student.

I undertake to obey the laboratory/study regulations and the instructions of the experimenter regarding safety, subject only to my right to withdraw declared above.

Signature *(participant)* ………………………………….. Date …………………..

*Print name ……………………………………………………………………………….*

Signature *(experimenter)* ………………………………. Date …………………..

*Print name …………………………………………………………………….……..*

## PAR-Q & YOU – A Questionnaire for People Aged 15 to 69

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

| YES | NO | | |
|---|---|---|---|
| ☐ | ☐ | 1 | **Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?** |
| ☐ | ☐ | 2 | **Do you feel pain in your chest when you do physical activity?** |
| ☐ | ☐ | 3 | **In the past month, have you had chest pain when you were not doing physical activity?** |
| ☐ | ☐ | 4 | **Do you lose your balance because of dizziness or do you ever lose consciousness?** |
| ☐ | ☐ | 5 | **Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?** |
| ☐ | ☐ | 6 | **Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?** |
| ☐ | ☐ | 7 | **Do you know of any other reason why you should not do physical activity?** |

**If you answered** ➔

## YES to one or more questions:

**Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.**

- **You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.**

↓

## NO to all questions:

**If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:**

- **start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.**
- **take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much**

➔

### DELAY BECOMING MUCH MORE ACTIVE:

- **if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or**
- **if you are or may be pregnant – talk to your doctor before you start becoming more**

**PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change**

## Informed Use of the PAR-Q:

The School of Sport, Health and Exercise Sciences has adapted this PAR-Q form for use of in conjunction with the Ethics Review and Approval form and informed consent for persons undertaking research which requires moderate to high-intensity physical activity. If you are in any doubt after completing this questionnaire, please consult your doctor prior to physical activity.

**You are encouraged to keep a copy of the completed PAR-Q form.**

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity programme or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME……………………………………………………………………………………………………

SIGNATURE…………………………………………………………….
DATE……………………………

SIGNATURE OF PARENT or GUARDIAN (for participants under 18 or vulnerable adults)

……………………………………………………………………………… DATE……………………………

SIGNATURE OF WITNESS

……………………………………………………………………………… DATE……………………………

**Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES top any of the seven questions overleaf.**

## EXAMPLE PRE-VISIT QUESTIONNAIRE

Bangor University
SCHOOL OF SPORT, HEALTH AND EXERCISE SCIENCES

Date ………………………………………………

| | |
|---|---|
| Have you taken any form of medication today? | Yes / No |
| Do you have any form of illness or infection? | Yes / No |
| Do you have an injury? | Yes / No |

Notes:

Within the last 24 hours:

| | |
|---|---|
| Have you avoided heavy / strenuous exercise? | Yes / No |
| Have you slept for 7 hours or longer? | Yes / No |
| Have you consumed alcohol? | Yes / No |
| Have you consumed the recommended intake of water? | Yes / No |

Notes:

Within the last 3 hours:

| | |
|---|---|
| Did you eat a light meal about 2 hours before the test? | Yes / No |
| Have you consumed any caffeine? | Yes / No |
| Have you smoked? | Yes / No |

Notes:

IF THE ANSWER TO ANY OF THE ABOVE IS 'YES', THEN YOU MUST CONSULT A MEMBER OF STAFF BEFORE UNDERGOING ANY EXERCISE TEST.

## EXAMPLE Menstrual Cycle Questionnaire

- At present which statement best describes your menstrual cycle?
  - ☐ I have regular periods: The date of the start of my last period was: ___ / ___ / _____
  - ☐ My periods are irregular: The date of the start of my last period was: ___ / ___ / _____
  - ☐ I do not have periods.

- Are you using the oral contraceptive pill/contraceptive patch/injection/implant/intra-uterine system?
  - ☐ Yes
  - ☐ No

  If yes, please specify which and give details (e.g. brand name)

  ________________________________________________

  If yes, has your contraception changed within the last 6 months?
  - ☐ Yes
  - ☐ No

- Please estimate the approximate duration of your menstrual cycle (the time from the start of one period to the start of your next period)?
  - ☐ Once every 20 days or less
  - ☐ Every 21 - 27 days
  - ☐ Every 28 - 35 days
  - ☐ Every 36 –50 days
  - ☐ Once every 4 months
  - ☐ Very irregular sometime skip several consecutive months

**Thank you for completing this questionnaire.**

# PARTICIPANTS INFORMATION SHEET CHAPTER 2

**School of Sport, Health**
**And Exercise Sciences**
George Building, Normal Site,
Bangor, Gwynedd
LL57 2PZ

# TITLE: The effect of personality on the exercise related brain activity of aerobic athletes

**Research Team:**

**Francesca Mottola –** pep83b@bangor.ac.uk
**Dr Anthony Blanchfield -** a.w.blanchfield@bangor.ac.uk
**Dr James Hardy**
**Dr Andrew Cooke**
SSHES, George Building, Bangor, Gwynedd, LL57 2PZ

## Invitation to Participate in a Research Study

As a healthy individual aged 18 - 50 who is engaged in relatively vigorous endurance exercise on at least one occasion per week (for example cycling, running or triathlon), you are being invited to take part in a research study. Before you decide to take part it is important for you to understand what is involved and why the research is being completed. Please carefully read the following information and ask the researchers any questions you may have. If you wish you can discuss with friends and relatives and take part at a later date if you wish to and spaces are still available. Thank you for reading.

## Background of the study

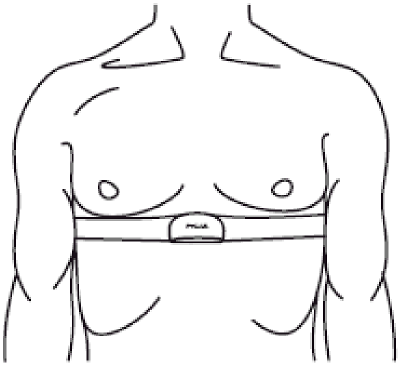
Surprisingly little is known about the way that exercise is effected by personality characteristics. This is particularly important for example in events that may involve two bouts of exercise in close proximity to each other for instance track cycling competitions, or during training days which involve two distinct bouts of exercise and is made even more unpredictable when individuals perform different activities in between these exercise bouts. We would like to investigate the effects of personality on the way that the brain responds to such a combination of tasks in terms of perceptions around exercise .We are doing this so that we can use these findings to later devise psychological interventions that individually accommodate the demands of such exercise scenarios.

## Participation in the study

You do not have to participant in the study if you do not wish to; providing consent to take part in the study is entirely voluntary. Should you provide consent to take part and then decide that you wish to withdraw, you are free to withdraw from the study at any time or for any reason without any explanation or reprisals. You should not take part in this study if you suffer from heart disease or are aware of any substantial risks that may mean you are more likely to encounter heart disease. Prior to taking part we will provide you with a questionnaire to assess this. If in conjunction with American College of Sports Medicine guidelines this questionnaire indicates that you have more than one risk factor for heart disease, unfortunately you will not be able to take part on this occasion. Due to the nature of the computerized tasks involved in this research you will unfortunately not be able to take part on this occasion if you are colour blind.

### What is required of you?

If you consent to take part, in total you will be required to make four visits to the exercise laboratories at the School of Sort, health and Exercise Sciences, Bangor University. Each visit will be composed of what would be regarded as vigorous to exhaustive. During the very first visit we will however also obtain a personality profile from you via some basic questionnaires. If you are female we will give you a basic questionnaire about your menstrual cycle and contraception. This is so as we can standardize your exercise visits and you can opt out of this in advance if you do not wish to answer this but still wish to take part in the study. Finally, we will measure your brain activity by attaching three painless and removable electrodes to your scalp. Two on the bones just behind the ear and one in the centre of your forehead. You will also wear a standard cap while we measure brain activity to which 4 further painless and removable electrodes will be attached We will also obtain some basic questionnaire data during all four visits regarding your mood and emotions, motivation and perceptions surrounding the exercise. We will also continuously measure your heart rate via a chest strap that will be placed approximately 1 inch below the breast bone, regardless of whether you are male of female **(See DIAGRAM).** You will fit the chest strap yourself after you have arrived at our laboratories but in a location that ensures your privacy.



During Visit 1, you will complete a maximal exercise test on a stationary bike. This test will increase in intensity (25 watts) every minute and you will voluntarily stop this exercise test when you feel like you can exercise no longer. This is to obtain your peak power output so as your exercise intensity can be standardised during your remaining visits. After this you will perform three simple computerized cognitive tasks. The first one will last for 5 minutes and will require to sequentially select via a computer keyboard the changing direction of an on screen arrow. The second one will also last for 5 minutes during which you will select a coloured key on a keyboard that matches one of four possible ink colours of written words that are presented one by one on a computer screen. Likewise the final one will last for 5 minutes and will require you to use your memory to perform a basic task of repeatedly remembering the letter of the alphabet that was presented on screen two letters back from the one that is displayed on at the time of you making your choice. This will be the end of Visit 1. (Approximately 60 minutes of your time).

You will then make three more visits to the same laboratory, all of these visits (known as conditions) will be made on separate days. The three visits (conditions) will take place in no particular order and during these three conditions, you will do the following:

Condition 1:

- Answer some basic questionnaires regarding your mood, emotions, motivation and personality.
- Repeat the five minute Computerized arrow task from Visit 1. This arrow task is performed to allow us to accurately record resting brain activity before exercise
- Perform a continuous 45 minute exercise task. This will consist of cycling for 15 minutes at 45% of your peak power, then cycling for 20 minutes at 65% of your peak power, and 10 minutes at approximately 60 – 80% of your peak power, where you will cover as much distance as possible. Fluctuations in your exercise intensity (power output) during this latter 10 minutes will therefore be determined by you.
- Provide a very small blood sample from your fingertip to measure your lactate. Lactate is found naturally in your blood and is used as standard measure of fatigue.
- Answer the same questionnaires as earlier in conjunction with some additional questions regarding your appraisal of the workload demands of the previous task.
- Spend 50 minutes on the three computer tasks that you completed in Visit 1 – again to record exercise related brain activity.
- Answer the same set of questionnaires as earlier, again including your evaluation of workload demands and recovery.
- Sit for 5-10 minutes before -answering the same set of questionnaires as earlier.
- Provide a very small blood sample from your fingertip to measure your lactate
- Perform a continuous exercise task that consists of cycling at 65% of your peak power until you feel exhausted and voluntarily decide to stop.

During the exercise, at set intervals, we will ask you to rate how effortful the exercise feels and we will measure your pedal revolutions. We also will measure your heart rate throughout the visit. (Approximately 3 hours - of your time).

Condition 2: This is identical to Condition 1 however instead of performing the 50 minute computer task you will watch a TV programme for 40 minutes, and perform the arrow computer task for 5 minutes either side of the programme. (Approximately 3 hours - of your time).

Condition 3: This is identical to Condition 1, however you will not perform the first 45 minute exercise task. (Approximately 2 hours and 15 minutes of your time).

**What are the benefits of taking part?**

We will give you £20 for taking part once you have completed your four visits. By completing the study you will also have the chance of winning either £300, £100, or £50 if you cover the most, second most or third most combined distance of all participants (approximately 20) across the two 10 minute time trials during Conditions 1 and 2. Similarly you can win a further £50 (i.e., up to a maximum of £150 across three separate visits) if you are able to cycle for the longest time of all participants during each visit when performing the continuous 65% peak power output task. As the exercise intensity in these cycling tasks has been standardized on a per participant basis, you stand a good chance of competing for these cash prizes regardless of your perceived training status.

By taking part in this study, you will also receive a free $VO_{2max}$ test. This is worth approximately £100. To further express our gratitude for your taking part in this experiment, in addition to the payment that you will receive, and the potential prize fund, , we will also offer you the opportunity to return to our laboratories in three to six months for another free non-research related $VO_{2max}$ test, should you wish to. However, this is not a requirement of the experiment so you are under no obligation to do so.

Francesca, the lead researcher on this project is also a cyclist and a qualified cycling coach. Therefore, as a further token of gratitude for completing your four visits, we will provide you with a free one hour consultation to discuss your $VO_{2max}$ scores and other training practices so as you can refine your training / nutrition strategies.

Finally, taking part also provides you with the opportunity to treat these laboratory sessions as very structured training sessions that have been specifically devised on sophisticated equipment by a sports science team.

**Are there any risks?**

As with any exercise you can encounter temporary physical and perceptual discomfort for very short periods. However due to the intensity of the exercise in our study this will be no different to the temporary discomfort that you may encounter during regular training or competition. For example a hilly bike ride, hill repetitions, or sprint interval repetition.

As with any vigorous exercise, regardless of where you perform it, it is possible that you could become unwell. To reassure you, the statistical likelihood of even severe events such as heart attack is very low and is reported to occur only once per 184,000 runners during events half-marathon (similar to your cycling exercise intensity here). Moreover, you are free to voluntarily stop exercising at any point. In the very unlikely event that something should occur with any of our participants in any study that we do here at SSHES, we have first aid trained staff and specialist equipment on hand. Arguably, our laboratory is therefore a much more controlled and safe environment for this type of exercise compared to what may be your more regular training setting out in the general environment.

There is a minor risk that you may encounter some skin irritation from the electrodes that we use to exercise related brain activity. For most participants, this will not cause any discomfort. In the very unlikely event that skin irritation occurs, please inform us and the experiment will immediately stop. An antihistamine tablet or cream (e.g., loratadine) can be used to alleviate any irritation. These are commercially available from supermarket and pharmacies. You may also encounter some mild and very temporary pain and or bruising when we obtain your lactate sample via finger prick procedure. We can assure you that this is a very standard practice with all of the studies like this that are performed in the UK and USA and that all blood samples are disposed of safely and collected via pre-sealed and unused devices. You may also encounter some temporary mental challenge during the 50 minute computer task. This will be no greater however than the type of activity that you may encounter during a mental work task that requires a lot of thought and/or concentration or a 2 hour lecture.

**Will my information be Confidential?**

All participant information will be stored on a secure password protected drive with only the researcher and supervisor named having access to this information. We may need to take your contact details so as we can liaise with you throughout the study. These details will however be stored in a locked filing cabinet and/or on a password protected computer with secure servers in a locked office on our University premises in the office of the lead researcher. For all of the data (questionnaires, performance measures etc) that we collect from you during the study your identity will be replaced with a unique code at the point of collection. We do this to comply to data protection standards so as nobody can identify you from your research data.

When you complete the study, or if you leave the study early, all of your information shall remain confidential and no information will be passed on to any third party for data gathering procedures, or advertisement. We may however seek to publish these findings in a peer-reviewed scientific journal. Should this happen we can assure you that you will be unidentifiable in any report or publication that may arise from this research.

### Who has approved this study?

This study has been approved by the research ethics committee of the School of Sport, Health and Exercise Sciences, Bangor University.

### Feedback of the Study

If at any point of the study you wish to provide feedback of your experience please ask the researcher for form 6. All feedback given to be sent to SSHES ethics committee, SSHES, Bangor University, Bangor, Gwynedd, LL57 2PZ. All information will be confidential. If you have any complaints be contact the Deputy Chair of the Ethics Committee Dr Hans-Peter Kubis, SSHES Ethics Committee c/o School of Sport, Health and Exercise Sciences, Bangor University, George Building, Bangor LL57 2PZ.

### Additional Questions

If you have any further questions about this research before deciding whether to take part please contact us on the details below:

**Francesca Mottola** – pep83b@bangor.ac.uk

# PARTICIPANTS INFORMATION SHEET CHAPTER 5

(Note that two ethics approvals were provided for each of the study of chapter 4 and 5. Here is reported the information sheet of the study presented in Chapter 5. In chapter 4 it the information sheet of Experiment 1A was slightly adjusted to reflect the control task, i.e., watching the video recording of the neurofeedback session. For this experiment, the information sheet included only 1 experimental session.)

PRIFYSGOL
BANGOR
UNIVERSITY

## TITLE: The effect of neurofeedback on endurance performance following self-regulation

### Research Team:

Francesca Mottola: pep83b@bangor.ac.uk
Anthony Blanchfield: a.w.blanchfield@bangor.ac.uk
Andrew Cooke: a.m.cooke@bangor.ac.uk
James Hardy: j.t.hardy@bangor.ac.uk

### Invitation

You are being invited to take part in a research study. Before you agree to take part it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and ask us if there is anything that is not clear or if you would like more information about the project and the procedures involved.

### Inclusion / exclusion criteria:

For the project we are recruiting right-handed, healthy males and females aged between 18 and 45.

If you want to take part in the project, you should be performing at least one intentional exercise session per week (including on occasion exercise which is regarded as vigorous. Unfortunately, on this occasion, you won't be able to take part in the project if you report two or more risk factors for CVD, if you have any mental or physical conditions – which may include CVD, diabetes, respiratory disorders, bronchitis, epilepsy, having encountered any form of lower limb muscle or joint injury in the last month, or if you are under medication that can temporarily affect your physical or mental state. Due to the nature of the written tasks, individuals with dyslexia will not be able to participate in the study at this time.

Upon your arrival in the laboratory you will be asked to fill and sign the medical questionnaires in which you should disclose any medical condition that you presently have and any medication that you are currently taking.

### What is the background of the study?

Neurofeedback is a **harmless non-invasive strategy** that is known to help individuals control their own brain activity. It is performed by attaching an electrode cap to the head in order to read and display, on screen, the electrical activity of the brain. Performing cognitive activity may mildly and temporarily (1 hr) alter one particular brain area affecting the individuals' performance on following physical tasks. The aim of the study is to target this brain area using neurofeedback training to assess whether neurofeedback can modify this response.

### Do I have to take part?

Remember that the decision to take part is entirely your own. Should you decide to take part you will be required to sign a participant consent form. However, on deciding to take part you will remain free to withdraw from the investigation at any point and without giving a reason. If you decide to withdraw, this will not affect your relationship with the School of Sport, Health, and Exercise Sciences or any of the researchers who are involved in the study. If you are a student, this will not affect the marks you receive, the outcome of your period of study at SSHES or your standing with your supervisor, other staff members or with the School. In this case, your data will be delated. If you do choose to withdraw, we will also try our best to delete the data that we have collected from you. However, this may not always be possible if your request occurs after we have anonymized data, analysed data, or published the research.

### What is required of me if I take part?

If you decide to take part in the study, you will be asked to attend three separate laboratory sessions which are performed at the School of Sport, Health and Exercise Sciences, Bangor University. This will involve maximal exercise and some questionnaires on momentary mood, self-control, motivation and personality. None of these questions are regarded as intrusive however you are free to skip any questions that you do not wish to answer, if they cause you discomfort.

### Visit 1: Duration – Approximately 1 hour

You will be briefed about the nature of the research and the commitments of taking part in the project and you will be asked to complete and sign the corresponding medical health questionnaires (examples accompanying this document) before completing and signing the informed consent form. Before doing so, you will have the opportunity to ask questions about the project and to designate your preferred times for the laboratory visits.

Following this, we will ask you to fill three psychological questionnaires related to behaviour and attitudes and will measure your body weight (performed by you) and height. You will then carry out a maximal incremental exercise test on a stationary bike. During this test the intensity (power output) will automatically increase (by 25 watts) every minute and you will voluntarily stop this exercise test when you feel like you can exercise no longer, i.e., you will continue to exercise until you reach your limit (exhaustion). This test will allow to obtain your peak power output that will be used to standardise your exercise intensity in the remaining visit. You will wear a facemask throughout the incremental test to collect gas expiratory exchanges to measure your oxygen consumption. This will not impede your breathing or your test performance.

During exercise we will record your heart rate via a chest strap that will be placed approximately 1 inch below the breast bone, regardless of whether you are male or female. You will fit the chest strap yourself after you arrive at our laboratories in a location that ensures your privacy. Throughout the task you will be asked to rate how effortful and strenuous the task feels with a scale ranging from 0 to 10.

## Visit 2 and Visit 3: Duration – Approximately 2 hours 30 minutes each

The visits are identical apart from the neurofeedback sessions that you receive. At the beginning of the session we will setup the equipment to measure your brain activity via electroencephalogram and muscular activity via superficial electromyography.

To record cortical activity, 3 painless and removable electrodes will be attached to your scalp, two on the bones just behind the ear and one in the centre of your forehead. You will also wear a standard cap to which 4 further painless and removable electrodes will be attached.

To record muscular activity, 3 removable electrodes will be attached to your right leg, 1 over the patella (just at centre of your knee joint) and 2 over the belly of the vastus lateralis (the muscle located on the external side of the anterior thigh).

Prior to the electrode's attachment, the sites will be cleaned with a a skin prep gel and swaps and then shaved with a disposable shaver. The shaved section will be about 40x 40 mm.

After this, the 2 visits will involve the following procedures:

- Basic questionnaires regarding your emotions and motivational state
- Recording of brain activity, followed by the recording of heart rate accomplished with a chest strap placed below your breast bone.
- Writing task where, in handwriting, you will copy the contents of an A4 page of written script.
- A second assessment of brain activity and heart rate followed by completion of the same questionnaires on emotion and motivation as the ones recorded at the beginning of the session.
- One of the two 18 minutes sessions of neurofeedback training in which you will be guided to control your brain activity using a visual display on a computer screen. To achieve this, you will see 2 bars on the computer screen that reflect your right and left side brain activity. Depending on whether it is Visit 2 or Visit 3, you will be trained to control the right and the left bar so as they are below/above a target line. In addition to the visual feedback, every time one of the bars does not meet the target criteria, you will hear a beep sound; hence you should silence the sound by maintaining both bars at the target level.
- After this, you will complete the questionnaires once more.
- Following the questionnaires, you will perform an exhaustive cycling task on a stationary bike at a constant percentage of your peak power output calculated from Visit 1. During this task, you will be asked to maintain a cadence between and 60 to 110 rpm and pedal until you feel exhausted and voluntarily decide to stop. During the exercise, at set intervals, we will ask you to rate how effortful the exercise feels and your affective state. We will also record your pedal revolutions, your heart rate and your muscular activity during the cycling test

- At the end of the time to exhaustion test, we will collect a small drop of blood from your earlobe to measure your blood lactate level. Lactate is found naturally in your blood and is used as standard measure of fatigue
- At the end of the visit, you will complete 3 further questionnaires.

**Summary of visits**

**Visit 1**

Project briefing

Medical screening

Consent form

Aerobic fitness test

**Visit 2 and Visit 3**

Questionnaires + brain activity and HR

Written task

Questionnaires + brain activity and HR

Neurofeedback

Questionnaires

Endurance Task

## What do I have to do?

- **48 hours** before each laboratory visit you will be asked to **avoid any strenuous exercise**
- **24 hours before each laboratory visit,** you will be asked **to avoid alcohol**
- **6 hours within each laboratory session,** you will be requested **to refrain** from any beverage that may contain **caffeine or others stimulants** (i.e. coca-cola, the, coffee, mocha, red-bull). You will also be asked to **avoid nicotine** at this time.
- Keep your **dietary patterns similar** for the 24 hours before each visit.
- Remember **to eat a light meal 2 hours** prior to the visits, but not within 2 hours.
- **bring/wear gym shorts, t-shirt or vest and trainers**. The laboratory is equipped with changing room and shower facilities for you to change before/after the session.

## What are the possible disadvantages and risks of taking part?

Participation in the study requires a specific time commitment to the 3 visits to the SSHES laboratory. As you will be required to cycle to exhaustion on each visit, for brief periods during each session during the physical tasks you may experience some temporary exertional discomfort. This will be no different to the discomfort that might be experienced during an intense or exhaustive exercise session and as a natural part of the experiment you will wear a heart rate belt at all times. As with any endurance-based exercise there is a minor risk of illness. To reassure you, the statistical likelihood of even severe events such as heart attack is very low and is reported to occur only once per 184,000 runners during events half-marathon (similar to your cycling exercise intensity here). Moreover, you are free to voluntarily stop exercising at any point. In the very unlikely event that something should occur with any of our participants in any study that we do here at SSHES, we have first aid trained staff and specialist equipment on hand. Arguably, the laboratory is therefore a much more controlled and safer environment for this type of exercise compared to what may be your more regular training setting out in the general environment.

There is a minor risk that you may encounter some skin irritation from the electrodes attached on the forehead and legs. For most participants, this will not cause any discomfort. In the very unlikely event that skin irritation occurs, please inform us and the experiment will immediately stop. An antihistamine tablet or cream (e.g., loratadine) can be used to alleviate any irritation. These are commercially available from supermarket and pharmacies. You may also encounter some mild and very temporary pain and or bruising when we obtain your lactate sample via earlobe prick procedure. We can assure you that this is a very standard practice with all of the studies like this that are performed in the UK and USA and that all blood samples are disposed of safely and collected via pre-sealed and unused devices.

### What are the possible benefits of taking part?

This study is based on a novel and cutting-edge scientific concept. By taking part you may as such be learning and carrying out performance based scientific strategies that are yet to be applied at any athletic standard anywhere in the world.

By taking part in this study, you will also receive a free $VO_{2max}$ test. This test provides an accurate measure of your current fitness level.

If you wish to, we can elaborate your aerobic profile and training zone guidance from your test. The feedback will be provided to you free of charge and will be similar to that offered by private facilities where a monetary fee of up to £100 is required for such a service.

### Confidentiality

As part of our standard procedures we will collect some basic health-based data from you. You will be required to verify this by placing your name on each form. This information will be accessible only to the named researchers on this project. It will also be stored securely in a locked office and away from any research data that may identify you. In the first instance we will also need to collect your name and may require some contact details from you so that we can arrange visit times. This too will be treated with the same confidentiality and security as your health data. All correspondence will take place through a password protected University e-mail account. For the purposes of any mobile phone correspondence, your name will be stored as a code. To comply with the general data protection regulation (GDPR, 2018), the data that we collect on you for research will be pseudoanonymized. This means that we will replace your name with a unique combination of numbers and letters to ensure that your research data does not publically identify you. The pseudoanonymized research data will be stored separately from any documents that contain your name or signature. All data will be discarded after a period of 5 years. All information will be stored in a locked office on the premises of the School of Sport, health and Exercise Sciences and on a password protected Bangor University computer, with secure servers.

When you complete the study, or if you leave the study early, all your information shall remain confidential and no information will be passed on to any third party for data gathering procedures, or advertisement. We may however seek to publish these findings in a peer-reviewed scientific journal. Should this happen we can assure you that you will be unidentifiable in any report or publication that may arise from this research. Any information which leaves the School will have your name and address removed so that you cannot be recognised from it.

### Who has reviewed the study?

This study has been approved by the research ethics committee of the School of Sport, Health and Exercise Sciences, Bangor University.

### Feedback on Conduct of Research

SSHES is always keen to hear the views of research participants about their experience. If you would like to feedback, please ask your researcher to provide you with Form 6 – Participant Feedback Form – from the Ethics Guidelines Handbook. Completion of this form is optional. The completed form should be returned to Dr Hans-Peter Kubis, Deputy Chair, Research Ethics Committee, SSHES, Bangor University, Bangor LL57 2PZ. All information will be treated in a strictly confidential manner.

You are also welcome to contact the University's assigned data protection officer (DPO) if for any reason, you wish to. The DOP of Bangor University can be contacted on these details: Mrs Gwenan Hine: gwenan.hine@bangor.ac.uk; 01248 382413

### Any Questions?

Please, contact us on the details below if you have any questions or you would like further information about the project.

You should not sign the form consenting to take part in the study if you still have unanswered questions or any doubts.

**Francesca Mottola** – pep83b@bangor.ac.uk

## PARTICIPANTS INFORMATION SHEET CHAPTER 3

(Note that two other information sheets were used for the data collection of this research project, here is reported only the one used for the data that are presented in chapter 3).

### 1 Study Title:

An investigation of training and recovery leading up to the Maratona dles Dolomites

### 2 Bangor University Research Team:

PhD Researchers: Francesca Mottola; Clare Barwood
Staff Researchers: Dr's Anthony Blanchfield, Andrew Cooke, James Hardy, Sam Oliver, and Ross Roberts

### 3 Invitation paragraph

As an entrant in the 2019 Maratone Dles Dolomites, you are being invited to take part in a research study. The information contained in this document will give you all of the details about the study. This document will also tell you what you will need to do if you would like to take part in the study. Please feel free to take your time to read the information carefully before deciding if you would like to take part. Though it is not a requirement, please also feel welcome to discuss whether you should take part with friends, relatives, or your Doctor. If you would like some more information, please just contact the individual named at the bottom of this document.

We would like to express our gratitude in advance for taking the time to read this document.

### 4 Requirements to take part in the Study

To take part in this study we require that you are able to understand written English and/or italian that you re 18 years of age or older. This research will be entirely questionnaire based. We will therefore never need to meet you, or to know who you are. The questionnaires will be answered by clicking on internet-links that will be automatically sent to you by e-mail on specific dates before and after the Maratona dles Dolomites. Because of this, you will need to be able to use a computer or smartphone to access these internet-links. So that we can send these internet-links to you on these dates, you will also need to provide us with your e-mail address when we ask for it.

## 5 What is the background of the study?

When people enter a cycling event, they generally take part in exercise training to prepare for that event. Up to 9000 people may take part in the Maratona dles Dolomites. With so many people taking part, the way that people prepare for the Maratona dles Dolomites will differ from person to person. This study will explore how general lifestyle (family, leisure, work) and personality are associated with the way that people train and recover when preparing for the Maratona dles Dolomites.

## 6 Do I have to take part?

After reading this document, it is up to you to decide whether or not you would like to take part in this study. If you decide to take part, you are free to withdraw at any time and without giving a reason. This will not affect your race entry in any way; it will also not affect your relationship with the race organisers, or with Bangor University.

If you would like to take part in this study, we will need your consent. To provide your consent you should place a tick next in the box that is placed next to "I consent" at the bottom of the webpage that contained this document.

As this study is questionnaire based, if you choose for some reason not to answer a specific question, we will also give you the chance to do so. This too will not affect your race entry in any way. It will also not affect your relationship with the race organisers, or with Bangor University.

## 7 What is required of me if I take part?

We will gather online questionnaire data from you at **four separate time-points.** These time points, and the requirements at each time-point, are listed below:

**Time-point 1** - After providing consent;
**Time-point 2** - Saturday 22nd June;
**Time-point 3** - Friday 5th July;
**Time-point 4** - Monday 8th July

In addition to these four time-points we will contact you **every day** beginning on Sunday 23rd June and ending on Saturday 6th July.

### Time-point 1 – After providing consent:

After consenting to take part, you will be asked to provide your e-mails address. You will then be required to answer some general questions about yourself. These questions will include:

- Age, gender, height, weight, and physical activity. We only ask for these details so that we can indirectly estimate your $\dot{V}O_{2max}$ ($\dot{V}O_{2max}$ is a common measure that we use to assess fitness in sport science).
- Your nationality, your first language and your previous participation in the Maratona dles Dolomites.
- After this, we will ask you approximately 100 questions about yourself. This will allow us to categorise certain aspects of your personality.
- We will ask you about how your coach influences your training (if you have one).
- For females, we will also ask you about your menstrual cycle (regularity, frequency, contraception use). We do this because s some of the things that we measure may change over time as a result of the menstrual cycle, e.g., mood. Importantly, as with all questions, you can skip this, if you wish to.

In total, Time-point 1 should take you approximately 20 - 30 minutes to complete.

**Time-point 2 – Saturday 22nd June:**

On **Saturday 22nd June**, you will receive an **e-mail** that contains a link to the questionnaires for this day. When you click this link in your e-mail, it will take you directly to these online questionnaires. The questionnaires in this link will ask you about your average training, recovery and general life for the previous two weeks:

- Your general training activity and your attitudes to training during this time
- Your average sleep quality and duration for the previous two weeks
- Your average mental fatigue for the previous two weeks
- Your average post-exercise and general recovery for the previous two weeks
- General things about your life stress and exercise for the previous two weeks
- We will also ask your expected race time in the 2019 Maratona dles Dolomites

In total, Time-point 2 should take you approximately 15 - 25 minutes. We courteously ask that you complete these questions for us on Saturday 22nd June.

**Time-point 3 – Friday 5th July:**

On **Friday 5th July**, you will receive an **e-mail** that contains a link to the questionnaires for this day. When you click this link in your e-mail it will take you directly to these online questionnaires. The questionnaires in this link will ask you:

- General things about your life stress and exercise for the previous two weeks
- We will also ask your expected race time in the 2019 Maratona dles Dolomites
- Here we will also ask you questions about your cycling motivations and goals

In total, Time-point 3 should take you approximately 15 -20 minutes. We courteously ask that you complete these questions for us on Friday 5th July.

**Time-point 4 – Monday 8th July:**

On **Monday 8th July**, you will receive an **e-mail** that contains a link to the questionnaires for this day. When you click this link in your e-mail it will take you directly to these online questionnaires. The questionnaires in this link will ask you for:

- Your actual race time, how effortful the race was, how recovered you are from the race, your motivations around the race.

In total, Time-point 4 should take you approximately 2 – 5 minutes. We courteously ask that you complete these questions for us as soon as possible, but not later than Wednesday 10th July.

**Daily contact: Sunday 23rd June – Saturday 6th July (14 days in total)**

Every morning between **Sunday 23rd June and Saturday 6th July**, you will receive an **e-mail** that contains a link to the questionnaires that you should complete for that day. When you click the link in your daily morning e-mail it will take you directly to the online questionnaires for that morning. The daily questionnaires will be identical for each of these 14 days and they will ask you to complete questions about:

- Your training and physical activity the day before;
- Your mental fatigue the day before;
- Your sleep the night before;
- Your recovery from exercise the day before (how recovered from exercise you were one hour after exercise, how recovered from exercise you were before bed, how recovered from exercise you were on waking this morning).
- We will also ask you for some simple psychological ratings from the day before (anxiety, fatigue vigour) and some psychological questions about your training session the day before (motivation, commitment, enjoyment, frustration)

The Daily questionnaires should take you approximately 5 – 12 minutes per day. We will send each questionnaire every morning daily. We courteously ask that you complete these questions for us as soon as possible after waking on each morning that they arrive.

## 8 What do I have to do?

We simply ask that you check your e-mail on each of the dates that are listed above and then access the link that is enclosed in each of those e-mails. The link that we send on each date will take you directly to the questions that we require you to answer for that day.

## 9 What are the possible disadvantages and risks of taking part?

Because of the subjective nature of questionnaires, it is possible that some people may find some questions intrusive. For instance, one question that we ask will require you to rate how often you felt depressed in the last two weeks. Another item asks you to choose between whether you like to be the centre of attention, or to blend in, while another questionnaire will ask you to rate your experiences around failure. For females, we will also ask you about your menstrual cycle. We would be grateful if you could answer each question very honestly.

However, we will also provide a tick selection to allow you to skip any questions that you choose to, if for some reason you decide not to answer. We would however also like to remind you at this point that your answers will be recorded anonymously.

We will be collecting data using an online programme, Qualtrics$^{XM}$. Qualtrics$^{XM}$ is commonly used in scientific research as a platform to collect questionnaire data when no direct contact is required with the person. Again, we would like to remind you that at no point will we collect your name; you will therefore complete these questionnaires anonymously. You can however access the security statement and privacy statement for Qualtrics$^{XM}$ by clicking on each blue link below:

Qualtrics$^{XM}$: Security statement
Qualtrics$^{XM}$: Privacy statement

## 10 What are the possible benefits of taking part?

For individuals who take part until the end of the study (i.e., complete the full study), we will provide you with feedback about the data that you provide to us. This means that we will be able to provide you with a report on your estimated $\dot{V}O_{2max}$, your personality characteristics, your training and recovery stress, and your general life stress. You will receive an automatic e-mail with a link to this report on, or after, the week of the 22nd of July. In addition, during the study we will use your daily data to provide you with feedback about your recovery and fatigue state. You will receive an automatic e-mail with a link to this report between the 1st and 3rd of July. Each of these reports might be helpful for you when you prepare for your next race. After the study is complete, we will also enter you into a random prize draw to receive 100 euros in Amazon vouchers. One separate winner at random will also gain a free race entry into the Maratona dles Dolomites in 2020. Only individuals who complete the full study will be entered into these prize draws. Should you win one of these prizes, we will inform you via the e-mail address that you provide to us. This is the only time that we will possibly use your e-mail for a reason other than to send you the link to the questionnaires that we would like you to complete, and your feedback.

## 11 Confidentiality and the use of my data

Only the named researchers on this document will have access to the data that you provide to us. We will capture your age, sex, height, weight, vocation and nationality. However, as we are collecting data anonymously (we will not be collecting your name), we do not expect these things to make you personally identifiable. We will need you to provide us with an e-mail address however after providing consent online. This is so that we can send out the daily questionnaires and the remaining questionnaire links on the dates of Friday 22nd June, Friday 5th July, and Monday 8th July, as well as your feedback. These e-mails will be sent directly to you by Qualtrics$^{XM}$. We will therefore not send you any group e-mails where other people may be able to see your contact information. Your e-mail information (or any other information) **will not** be passed on for any third party use. The only other time that we may use your e-mail is to e-mail you directly if you have won our prize draw. We will only inform the winner of this.

Once we compile your anonymous data for data analysis, we will store it under a code name on password protected Bangor University Servers and in a Bangor University Secured one-drive folder that will only be available to the researchers who are named at the top of this document. We will store your data for 5 years from the end of data collection. While we will do our utmost to delete your data, should you decide to withdraw from the study. However, as the data that we collect will be anonymised and coded, we cannot guarantee that we will be able to do this after data collection has taken place. We make seek to publish the findings in an academic publication. They will also be used as part of a Doctorate thesis. We guarantee that you will not be personally identifiable from any of this data.

### 12 Who is organising or funding the research? (if applicable)

This research is part of a Bangor University PhD research project and is partly funded by a European Union Knowledge Economy Skills Scholarships European Convergence programme. Details about this programme can be found below:

Bangor University Knowledge Economy Skills Scholarships

### 13 Who has reviewed the study?

This study has been reviewed by the Local Research Ethics Committee in the School of Sport, Health and Exercise Sciences, Bangor University

### 14 Feedback on Conduct of Research

The School of Sport, Health and Exercise Sciences is always keen to hear the views of research participants about their experience. If you would like to feedback, please ask your researcher to provide you with Form 6 – Participant Feedback Form – from the Ethics Guidelines Handbook. Completion of this form is optional. That form, or any concerns or complaints about this study, or the conduct of individuals conducting this study, should be referred to:

College Manager, College of Human Sciences, Bangor University, Bangor, Gwynedd LL57 2AS; or, e-mail: huw.ellis@bangor.ac.uk.

You are welcome to contact the University's assigned data protection officer (DPO) if for any reason, you wish to. The DOP of Bangor University can be contacted on these details: Mrs Gwenan Hine: gwenan.hine@bangor.ac.uk; 01248 382413.

### 15 Any Questions?

Please ask if you have any questions. You should not consent to taking part in the study if you have unanswered questions or any doubts. If you have any questions about the study, please direct them to the individual below:

### 16 Contact: Francesca Mottola: pep83b@bangor.ac.uk

# APPENDIX B

## QUESTIONNAIRES and TASKS

## THE BRUNEL MOOD SCALE (BRUMS)

## (Chapter 2 and 4)

***Terry et al., 2003***

Below is a list of words that describe feelings. Please read each one carefully. Then cross the box that best describes **HOW YOU FEEL RIGHT NOW**. Make sure you answer every question.

**0 = not at all 1 = a little 2 = moderately 3 = quite a bit 4 = extremely**

| | | **0** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|---|---|
| 1. | Lively | ☐ | ☐ | ☐ | ☐ | |
| 2. | Worn out | ☐ | ☐ | ☐ | ☐ | |
| 3. | Annoyed | ☐ | ☐ | ☐ | ☐ | ☐ |
| 4. | Exhausted | ☐ | ☐ | ☐ | ☐ | ☐ |
| 5. | Sleepy | ☐ | ☐ | ☐ | ☐ | ☐ |
| 6. | Bitter | ☐ | ☐ | ☐ | ☐ | ☐ |
| 7. | Energetic | ☐ | ☐ | ☐ | ☐ | ☐ |
| 8 | Angry | ☐ | ☐ | ☐ | ☐ | ☐ |
| 9. | Active | ☐ | ☐ | ☐ | ☐ | ☐ |
| 10. | Tired | ☐ | ☐ | ☐ | ☐ | ☐ |
| 11. | Bad Tempered | ☐ | ☐ | ☐ | ☐ | ☐ |
| 12. | Alert | ☐ | ☐ | ☐ | ☐ | ☐ |

**PANAS (short version)**

**(Chapter 2 and 5)**

***Watson & Clark, 1998; Mackinnon et al., 1999***

This scale consists of a number of words that describe different feelings and emotions. Read each item and then circle a number from the scale below next to each word. Indicate to what extent you feel this way **right now**, that is, at the present moment.

| **RIGHT NOW…** | **Strongly disagree** | | | | | **Strongly agree** |
|---|---|---|---|---|---|---|
| **1. I am Inspired** | 1 | 2 | 3 | 4 | 5 | 6 |
| **2. I am Alert** | 1 | 2 | 3 | 4 | 5 | 6 |
| **3. I am Excited** | 1 | 2 | 3 | 4 | 5 | 6 |
| **4. I am Enthusiastic** | 1 | 2 | 3 | 4 | 5 | 6 |
| **5. I am Determined** | 1 | 2 | 3 | 4 | 5 | 6 |
| **6. I am Afraid** | 1 | 2 | 3 | 4 | 5 | 6 |
| **7. I am Upset** | 1 | 2 | 3 | 4 | 5 | 6 |
| **8. I am Nervous** | 1 | 2 | 3 | 4 | 5 | 6 |
| **9. I am Scared** | 1 | 2 | 3 | 4 | 5 | 6 |
| **10. I am Distressed** | 1 | 2 | 3 | 4 | 5 | 6 |

## Challenge-threat State

(Chapter 2)

*Moore et al., 2013*

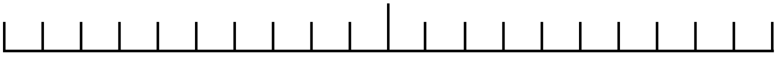
<table>
<tr><td colspan="6"><b>How demanding do you expect the next cycling time-to-exhaustion test to be?</b></td></tr>
<tr><td><b>Not at all demanding</b></td><td></td><td></td><td></td><td></td><td><b>Extremely demanding</b></td></tr>
<tr><td><b>1</b></td><td><b>2</b></td><td><b>3</b></td><td><b>4</b></td><td><b>5</b></td><td><b>6</b></td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="6"><b>How able are you to cope with the demands of the cycling time-to-exhaustion?</b></td></tr>
<tr><td><b>Not at all able</b></td><td></td><td></td><td></td><td></td><td><b>Extremely able</b></td></tr>
<tr><td><b>1</b></td><td><b>2</b></td><td><b>3</b></td><td><b>4</b></td><td><b>5</b></td><td><b>6</b></td></tr>
</table>

## NASA Task Load Index

## (Chapter 2)

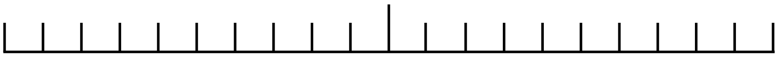
We are interested in measuring the experience you had during the task, namely the “workload” you experienced. The factors that influence your experience of workload may come from the task itself, your feelings about your own performance, how much effort you put in or the stress and frustration you felt. Since workload is something that is experience individually, there are not effective rulers that can be used to estimate the workload of different activities. Because workload may be due to different factors, we will evaluate several of them individually with a set of six scales. You will evaluate your experience during the task by putting an “X” on each scales at the point that best match your experience. Each line has two endpoints, please be aware that the “performance scale” goes from “good” left to “bad” right. Consider each scale individually.

**How mentally demanding was the task?** (How much mental and perceptual activity was required? Was the task easy or demanding simple or complex, exacting or forgiving?)



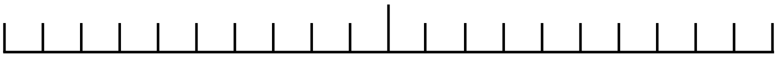
Very Low Very High

**How physically demanding was the task?** (How much physical activity was required? Was the task easy or demanding, slow or brisk, slack or strenuous?)



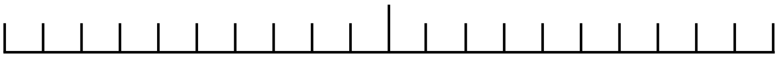
Very Low Very High

**How hurried or rushed was the pace of the task?** (How much time pressure did you feel due to the rate or pace at which the task occurred? Was the pace slow or rapid and frantic?)



Very Low Very High

**How successful were you in accomplishing what you were asked to do?** (How successful do you think you were in reaching the goal of the task? How satisfied were you with your performance?)



Perfect Failure

**Effort.** How hard did you have to work (mentally and physically) to accomplish your level of performance?

Very Low Very High

**Frustration.** How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content and relaxed did you feel during the task?

Very Low Very High

**Perceived Recovery Scale**

**(Chapter 2)**

***Laurent et al., 2011***

| | |
|---|---|
| **10** | **Very well recovered / Highly energetic** |
| **9** | |
| **8** | **Well recovered / Somewhat energetic** |
| **7** | |
| **6** | **Moderately recovered** |
| **5** | **Adequately recovered** |
| **4** | **Somewhat recovered** |
| **3** | |
| **2** | **Not well recovered / Somewhat tired** |
| **1** | |
| **0** | **Very poorly recovered / Extremely tired** |

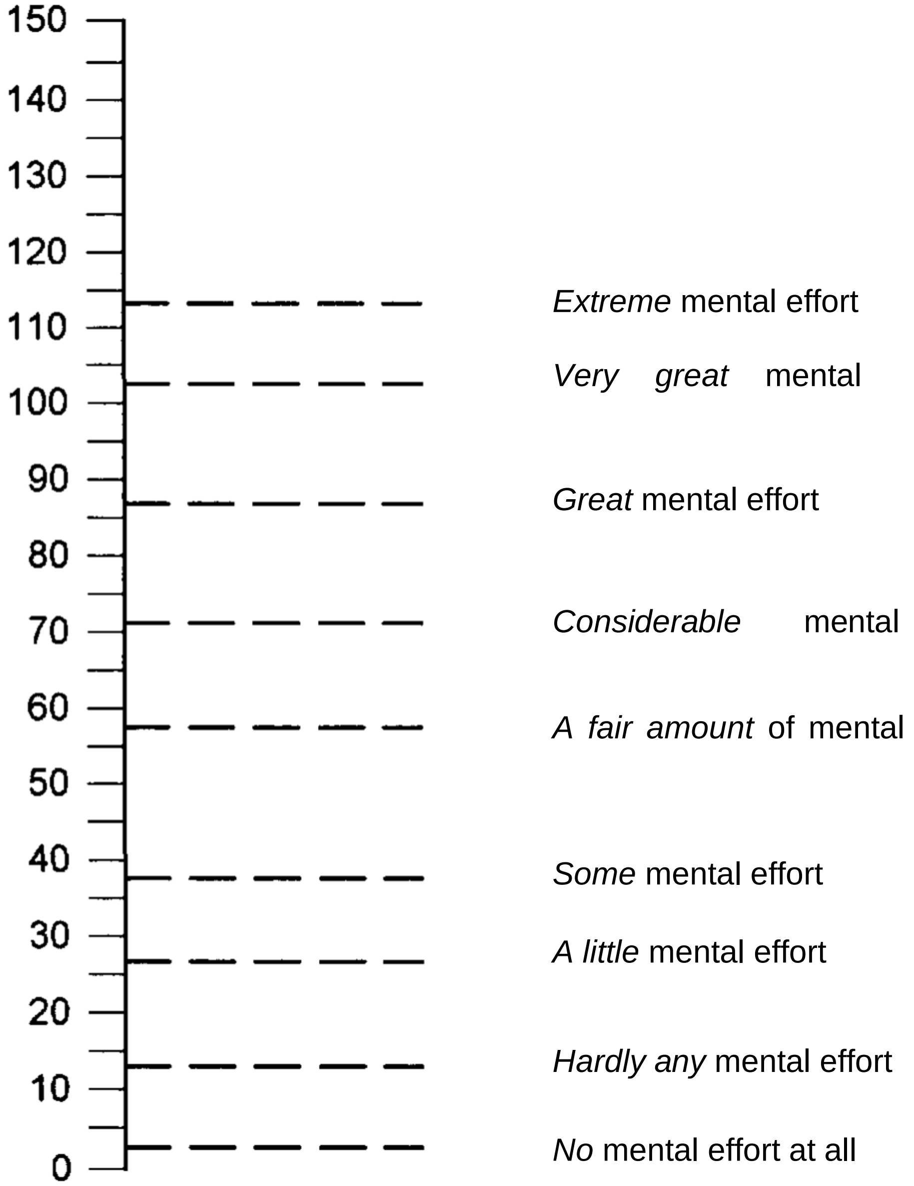
## RATING SCALE OF MENTAL EFFORT

**(Chapter 2)**

***Zijlstra, 1993***

Mental effort is described by Zijlstra (1993) as the amount of mental resources (focus) that one applies to a task.

Please mark an **‘X’** on the scale to indicate **your level of mental effort** during the task you have just performed. You will not be judged on the information that you give here. Please respond honestly.



**STATE OF SELF CONTROL CAPACITY SCALE (SHORT VERSION)**

**(Chapter 4 and 5)**

***Ciarocco et al., 2007***

**SSCCS.** Read each sentence and then circle a number from the scale below next to each word. Indicate to what extent you feel this way **<u>right now</u>**, that is, at the present moment**.**

| **Right Now…** | **Not True 1** | **2** | **3** | **4** | **5** | **6** | **Very True 7** |
|---|---|---|---|---|---|---|---|
| **I need something pleasant to make me feel better.** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **I feel drained.** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **If I were tempted by something right now, it would be very difficult to resist.** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **I would want to quit any difficult task I was given.** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **I feel calm and rational.** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **I can't absorb any information.** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **I feel lazy.** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **I feel sharp and focused.** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **I want to give up.** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **I feel like my willpower is gone.** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |

## MOTIVATION (TASK PERFORMANCE)

## (Chapter 5)

*Matthews et al., 2001*

| | Not at all | A little bit | Some-what | Very much | Extremely |
|---|---|---|---|---|---|
| **I expect the content of the task will be interesting** | 0 | 1 | 2 | 3 | 4 |
| **The only reason to do the task is to get an external reward (e.g. payment)** | 0 | 1 | 2 | 3 | 4 |
| **I would rather spend the time doing the task on something else** | 0 | 1 | 2 | 3 | 4 |
| **I am concerned about not doing as well as I can** | 0 | 1 | 2 | 3 | 4 |
| **I want to perform better than most people do** | 0 | 1 | 2 | 3 | 4 |
| **I will become fed up with the task** | 0 | 1 | 2 | 3 | 4 |
| **I am eager to do well** | 0 | 1 | 2 | 3 | 4 |
| **I would be disappointed if I failed to do well on the task** | 0 | 1 | 2 | 3 | 4 |
| **I am committed to attaining my performance goals** | 0 | 1 | 2 | 3 | 4 |
| **Doing the task is worthwhile** | 0 | 1 | 2 | 3 | 4 |
| **I expect to find the task boring** | 0 | 1 | 2 | 3 | 4 |
| **I feel apathetic about my performance** | 0 | 1 | 2 | 3 | 4 |
| **I want to succeed on the task** | 0 | 1 | 2 | 3 | 4 |
| **The task will bring out my competitive drives** | 0 | 1 | 2 | 3 | 4 |
| **I am motivated to do the task** | 0 | 1 | 2 | 3 | 4 |

## ATTENTIONAL FOCUS

**(Chapter 5)**

***Brick et al., 2014; 2016***

Please, indicate how frequently you focused on thoughts from each of the category below during the cycling time to exhaustion test

Did you use any of the active self-regulation thought examples listed here during the cycling time to exhaustion? If yes could you elaborate? (relaxing, chunking, self-talk, mantras, improving cycling techniques, cadence rhythm, mindfulness, objectives, targets imagery or visualization, counting, meditation):

| **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Never | Almost never | Rarely | Seldom | Sometimes | Occasionally | Often | Frequently | Most of the time | Always almost | Always |

Did you use any of the internal monitoring thought examples listed here during the cycling time to exhaustion? If yes could you elaborate? (e.g. overall effort, bodily sensations, e.g. exertional pain, muscle soreness, fatigue breathing, temperature, thirst, perspiration, heart rate, pain):

| **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Never | Almost never | Rarely | Seldom | Sometimes | Occasionally | Often | Frequently | Most of the time | Always almost | Always |

Did you use any of the outward monitoring thought examples listed here during the cycling time to exhaustion? If yes could you elaborate? (cycle-ergometer noise, lab conditions – temperature, features, equipment):

| **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Never | Almost never | Rarely | Seldom | Sometimes | Occasionally | Often | Frequently | Most of the time | Always almost | Always |

Did you use any of the distractive thoughts examples listed here during the cycling time to exhaustion? If yes could you elaborate?

(intentional switching off, imagined distractive music, reflective thoughts, irrelevant day-dreams, etc):

| **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Never | Almost never | Rarely | Seldom | Sometimes | Occasionally | Often | Frequently | Most of the time | Always almost | Always |

## INTRINSIC MOTIVATION INVENTORY (EFFORT & ENJOYMENT)

## (Chapter 5)

***McAuley et al., 1988***

**IMI**. Thinking about the cycling time to exhaustion test that you have just performed, please, indicate how true it is for you each of the statements using the following scale.

| | **Not At All True** | | | **Some-what True** | | | **Very True** |
|---|---|---|---|---|---|---|---|
| **I put a lot of effort into the task** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **I didn't try very hard to do well** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **I tried very hard on this task** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **It was important to me to do well** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **I didn't put much energy into this** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |

## Written tasks

## (Chapter 4 and 5)

For this task, you will copy the following text by hand onto the lined piece of paper provided.

However, when you find a word that includes the letter A, the letter N or both please, omit any of the two letters while writing the word.

For example if you find the word 'SECOND' you should write 'SECOD', if you find the word 'ADVANTAGE' you should report 'DVTGE'.

Written task 1

Stars are the fundamental units of luminous matter in the universe, and they are responsible, directly or indirectly, for most of what we see when we observe it. They also serve as our primary tracers of the structure and evolution of the universe and its contents. Consequently, it is of central importance in astrophysics to understand how stars form and what determines their properties. The generally accepted view that stars form by the gravitational condensation of diffuse matter in space is very old, indeed almost as old as the concept of universal gravitational attraction itself, having been suggested by Newton in 1692. However, it is only in the past half-century that the evidence has become convincing that stars are presently forming by the condensation of diffuse interstellar matter in our Galaxy and others, and it is only in recent decades that we have begun to gain some physical understanding of how this happens. Observations at many wavelengths, especially radio and infrared, have led to great advances in our knowledge of the subject, and the observational study of star formation is now a large and active field of research. Extensive theoretical and computational work has also contributed increasingly to clarifying the physical processes involved. Star formation occurs as a result of the action of gravity on a wide range of scales, and different mechanisms may be important on different scales, depending on the forces opposing gravity. On galactic scales, the tendency of interstellar matter to condense under gravity into star-forming clouds is counteracted by galactic tidal forces, and star formation can occur only where the gas becomes dense enough for its self-gravity to overcome these tidal forces, for example in spiral arms. On the intermediate scales of star-forming 'giant molecular clouds' (GMCs), turbulence and magnetic fields may be the most important effects counteracting gravity, and star formation may involve the dissipation of turbulence and magnetic fields. On the small scales of individual prestellar cloud cores, thermal pressure becomes the most important force resisting gravity, and it sets a minimum mass that a cloud core must have to collapse under gravity to form stars.

A= 142; N = 100

Written task 2

Most of the star formation in galaxies occurs in spiral arms, which are marked primarily by their concentrations of luminous young stars and associated glowing clouds of ionized gas. The most luminous stars have lifetimes shorter than ten million of year, or ten −three times the age of the universe, so they must have formed very recently from the dense interstellar gas that is also concentrated in the spiral arms. Star formation occurs also near the centres of some galaxies, including our own Milky Way galaxy, but this nuclear star formation is often obscured by interstellar dust and its existence is inferred only from the infrared radiation emitted by dust heated by the embedded young stars. The gas from which stars form, whether in spiral arms or in galactic nuclei, is concentrated in massive and dense ‘molecular clouds’ whose hydrogen is nearly all in molecular form. Some nearby molecular clouds are seen as ‘dark clouds’ against the bright background of the Milky Way because their interstellar dust absorbs the starlight from the more distant stars. In some nearby dark clouds many faint young stars are seen, most distinctive among which are the T-Tauri stars, whose variability, close association with the dark clouds, and relatively high luminosities for their temperatures indicate that they are extremely young and have ages of typically only about 1 million year. These T-Tauri stars are the youngest known visible stars, and they are ‘pre-main-sequence’ stars that have not yet become hot enough at their centres to burn hydrogen and begin the main-sequence phase of evolution. Some of these young stars are embedded in particularly dense small dark clouds, which are thus the most clearly identified sites of star formation. These clouds have been studied extensively, using radio techniques to observe the heavier molecules such as CO and infrared techniques to study the dust. Observations of the thermal emission from the dust at far-infrared wavelengths have proven to be particularly useful for studying the structure of these small star-forming clouds; the dust is the best readily observable tracer of the mass distribution because most of the heavier molecules freeze out onto the dust grains at high densities.

$A = 137$; $N = 99$