The Psychology of Endurance Performance

Robert Hyland-Monks

Edge Hill University

A thesis submitted in partial fulfilment of the requirements of
Edge Hill University for the degree of
Doctor of Philosophy

August 2022

Author Acknowledgments

Friedrich Nietzsche said, “A few hours of mountain climbing make a blackguard and a saint two rather similar creatures.” There are many trials and tribulations to completing a PhD, and I now understand and respect the sacrifices required. Through this journey, a circle of good people around me was vital to maintaining my sanity. So, I wanted to pay thanks to those people here.

Firstly, I would like to thank Dr David Marchant and Dr Lorcan Cronin. You have offered the unwavering support and critical eye I have needed. Thank you for the time and energy you have dedicated to helping me.

I would also like to thank my parents. You instilled in me the importance of education and have always believed in my potential. I do not think I would be completing a PhD without you in my life.

Lastly, my gratitude extends to every participant who willingly gave up their free time to participate in my research.

Author Notes

As experienced by many of my peers, the pandemic created a multitude of challenges to producing in-person research. When the first lockdown was announced in 2020, my supervisory team and I were forced to rethink our plans for the remainder of this program of research. This resulted in a new research agenda that did not require in-person research, culminating in a systemic review (Chapter 4), a case study in place of an experiment (Chapter 5), and a research project conducted remotely (Chapter 6).

General Abstract

The understanding of physical performance and the limits of fatigue in man have been subject to research for over 100 years, but only in more recent decades has attention turned to psychology and the cognitive components of exercise tolerance and self-regulation of effort. The overarching aim of this project of research was to investigate the self-regulation of endurance performance by utilising contemporary research methods. In doing so, the feasibility of using these methodologies to achieve this aim was also subject to investigation. Firstly, a mixed-methods approach using the think aloud protocol was adopted to observe the thought processes of cyclists during exercise, while also investigating the potential for this methodology to interfere with task performance. The following chapter features a positional argument for executive function and the prefrontal cortex (PFC) as central to the self-regulation of endurance performance. Subsequently, a systematic review of literature is presented on the use of functional near-infrared spectroscopy (fNIRS) to study PFC oxygenation during self-paced exercise performance, reviewing both the methodology itself and study findings. A case study is then presented of best-practice use of fNIRS to investigate the influence of performance feedback and task knowledge on cycling performance and PFC haemodynamics. Finally, a field study exploring the self-regulatory capacities of endurance performers in real-world settings is presented.

Keywords: cognition, cycling, executive function, prefrontal cortex, functional near infrared spectroscopy, pacing, running, self-regulation, think aloud, time-trial

Contents

List of Tables

List of Figures

Abbreviations

ACC – anterior cingulate cortex

BDNF – brain-derived neurotrophic factor

CGM – central governor model

Cox – cerebral oxygenation

DPF – differential pathlength factor

EEG – electroencephalogram

ET – endurance trained

fNIRS – functional near-infrared spectroscopy

HHb – deoxygenated haemoglobin

IHE – intermittent hypoxic exposure

LI = laterality index

NASA TLX – National Aeronautics and Space Administration Task Load Index

KI – known incline

Non-ET – non-endurance trained

nTHI – normalized tissue haemoglobin index

O_2Hb – oxygenated haemoglobin

PFC – prefrontal cortex

PO – power output

PRISMA – Preferred Reporting Items for Systematic Review and Meta-Analyses

RAH – reticular-activating hypofrontality

ROI – region of interest

RPE – rating of perceived exertion

rPO – relative power output

RT – reaction time

TA – think aloud

tCDS – transcranial direct current stimulation

tHb – total haemoglobin

TOI – tissue oxygenation index

TT – time-trial

TTBL – baseline time-trial

TTFull – time-trial with full feedback

TTNoFB – time-trial with no feedback

TTNoPro – time-trial with no course profile and distance feedback

UI – unknown incline

VO_{2max} – maximal oxygen consumption

VO_{2peak} – peak oxygen consumption

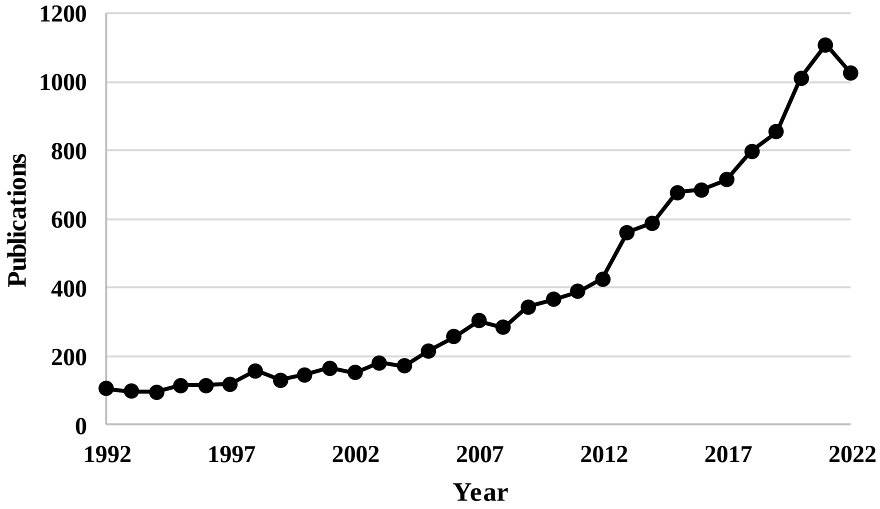
W_{max} – maximal work capacity

Chapter 1 Introduction

Interest in Endurance Performance

In the broadest sense, endurance exercise is defined by whole-body, dynamic exercise that involves a continuous effort lasting for 75 seconds or longer (McCormick et al., 2019). Participation in endurance events has risen significantly in recent years. A record 43,000 people registered to participate in the London Marathon in 2019, toppling the record set the previous year (London Marathon, 2019). Furthermore, since the inaugural RideLondon-Surrey Sportive in 2013, there has been an increase in registered participants year-on-year, with over 100,000 cyclists signing up in 2017 (Walker, 2017). In addition, since its inception in 2005, Parkrun UK has transitioned from running one event to organising a total of 768 5 km runs across the UK per week (Parkrun, 2022).

Figure 1.1 PubMed Publication Count Between 1992-2022 Featuring ‘Endurance’ and ‘Performance’ Within the Title and Abstract.



The growth in popularity of endurance events is reflected in the exponential growth in recent years of research conducted to further our understanding of endurance performance. To demonstrate this, a search term analysis of publication titles in the SPORTDiscus database using the words ‘endurance’ and ‘performance’ returned 1457 articles, of which 285 (19.6%) were published within the last five years. Moreover, a title and abstract search term analysis of the PubMed database revealed a distinct upward trend in publications in recent years (Figure 1.1). Although one would expect an increase in research output as the field of sport science grows over time, this recent substantial growth in research concerning endurance performance demonstrates a particular, heightened interest in recent times.

This interest is driven by the importance of such research from the top to the bottom of the participation pyramid. For instance, aerobic exercise has clear benefits to both physical (Posadzki et al., 2020) and cognitive health (Erickson & Kramer, 2008). Likewise, an understanding of the physiological determinants of endurance performance (Joyner & Coyle, 2008) could help guide advances in training methods and talent ID programs.

Pacing of Endurance Performance

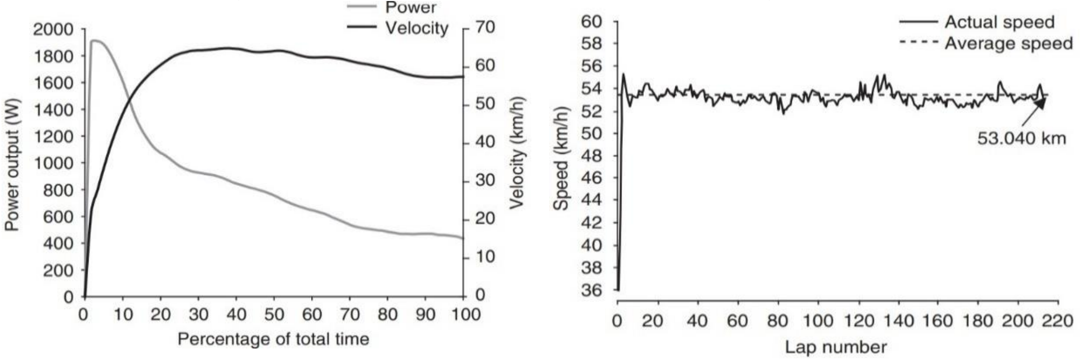
Pacing has been conceptualised as the optimal management of resources across an exercise task to achieve one's objective (Foster et al., 1994). Athletes have the volitional control to select from all exercise intensities, ranging from rest to maximal effort possible at any given moment (Renfree & Casado, 2018). Effective pacing is crucial to endurance performance; for instance, a high motivational drive could be indulged without due regard for homeostatic control, risking premature neuromuscular failure (St. Clair Gibson et al., 2013). In contrast, pacing which is too conservative will result in a greater chance of race completion, but underutilization of resources, resulting in underperformance through sub-optimal pacing. In addition, the importance of pacing to endurance performance is evident in the absence of the intellectual capacity to self-regulate effort. Research has demonstrated that elite runners with intellectual impairments (i.e., an intellectual quotient ≤ 75) exhibited greater velocity fluctuations in 400 m and 1500 m running events when compared to athletes without intellectual impairments, and when compared to pacing profiles exhibited in world-record performances (Van Biesen et al., 2016).

Several studies have recently investigated the pacing strategies of endurance performers (e.g., Abbiss & Laursen, 2008; Angus, 2014; Hanley, 2014, 2015; Renfree et al., 2016; Renfree & St. Clair Gibson, 2013; Van Biesen, et al., 2016). Abbiss and Laursen (2008) provide a comprehensive overview of pacing strategies adopted in competition as a function of event duration and length (Figure 1.2). Firstly, under stable conditions (e.g., consistent weather and flat terrain), a constant pace is preferable for events lasting above 2 minutes. This is evident in a 1-hour track cycling world record attempt (Figure 1.2b), as the athlete maintains a constant pace, with a conscious effort to ensure little variation from target speed (53 km/hour). For events shorter than 30 seconds, an 'all-out' pacing strategy may be optimal (Figure 1.2a). In such events, participants often spend a large percentage of the event in the acceleration phase and therefore at submaximal speed, before reaching peak velocity and gradually declining (Wilberg & Pratt, 1988). Given the above and the fact that the kinetic energy required in the acceleration phase is disproportionately greater than maintaining velocity (van Ingen Schenau et al., 1992), this phase is crucial to performance. Furthermore, given the duration of the event, conscious decision-making with respect to a pacing strategy is done pre-performance with little room for adjustment in-event.

Figure 1.2 Observed Pacing Strategies in Endurance Performance.

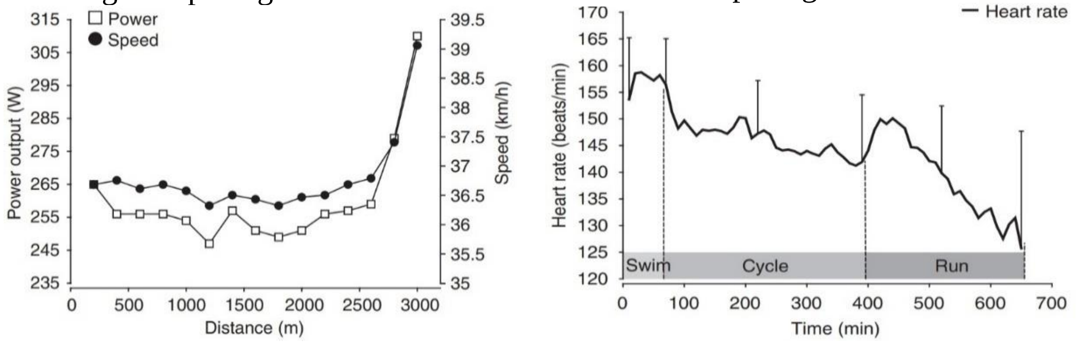
2a. All-out pacing

2b. Even pacing

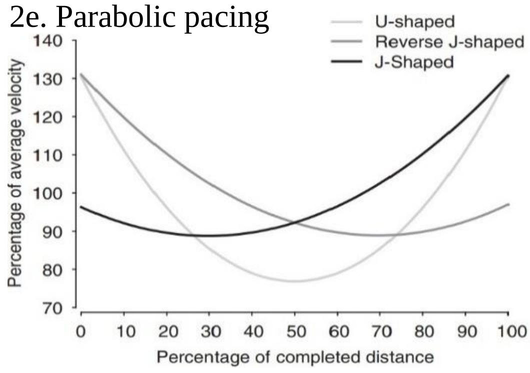


2c. Negative pacing

2d. Positive pacing



2e. Parabolic pacing



Note. Reused with permission from Abbiss and Laursen (2008).

Other pacing strategies have been documented for a variety of endurance disciplines. A negative pacing profile (Figure 1.2c) is often observed for middle-distance events (e.g., running > 3000 m) and is generally characterized by a progressively faster pace across the duration of the event. This strategy is thought to be effective as it reduces the risk of premature failure through preserving carbohydrate levels (Abbiss & Laursen, 2005) and preventing excessive oxygen consumption (Sandals et al., 2006) in the earlier stages of a race. Conversely, a positive pacing profile (Figure 1.2d) is characterized by a progressively slower pace across the duration of the event and is often exhibited in shorter swimming and rowing events, presumably due to the relatively short time spent in the acceleration phase. It is considered a riskier strategy given the greater oxygen uptake, fatiguing metabolites accumulated and higher rating of perceived exertion (RPE) observed (Thompson et al., 2003). In addition, a positive profile is often observed in ultra-endurance events, which is thought to occur due to glycogen depletion and alterations in substrate utilization, neuromuscular fatigue, and rising perceived fatigue and exertion levels over the duration of the event (Abbiss & Laursen, 2005). However, given the complexity and variability of these events, it is difficult to assess pacing strategies. Lastly, more contemporary commentary has highlighted a potential oversimplification of pacing strategies described above. This commentary includes ‘J-’, ‘U-’, and ‘reverse J-shaped’ pacing strategies (Figure 1.2e), whereby athletes tend to reduce pace from the start of the event before increasing pace in the latter stages. These pacing strategies are typically characterized by an end-spurt: a reservation of energy which enables a tactical increase in pace in the latter stages of a race (Tucker et al., 2006).

Moving on, Renfree and St. Clair Gibson (2013) presented evidence to demonstrate how pacing strategies explain variance in endurance performance. Competitors in the 2009 IAAF Marathon Championship were split into quartiles based on their finishing times. Group one finishers ran a significantly lower percentage of their personal best speed in the first 10 km, and a higher percentage from 35 km onwards compared to the other groups. Moreover, a smaller variation in mean speed was evident for group one finishers relative to their competitors. Thus, a more even pacing strategy, with little requirement for adjustment, would appear to be most optimal for a marathon. Groups two, three and four exhibited a more pronounced positive pacing profile: the second half of the race ran at a slower pace than the first. Thus, it is feasible to suggest that lower-placing runners selected initial running speeds that were unsustainable for the entire race, compromising performance and leaving less room for error. The findings were extended to an analysis of a 100 km World Masters Championship race, examining the pacing profiles of senior (age > 40 years) competitors (Renfree et al., 2016). In addition, Angus (2014) has analysed two recent in-competition achievements of marathon world records. Although there was little appreciable slowing of pace throughout both efforts analysed, both runners opted for different pacing strategies. One runner exhibited a parabolic U-shaped pacing strategy; while the other runner exhibited a sinusoidal (i.e., oscillatory) pacing strategy. As our understanding of pacing advances, we may better comprehend these differences. For instance, research has found athletes select a pacing strategy in line with their physiological condition (Hettinga et al., 2012).

Alongside running, researchers have also investigated optimal pacing strategies across various distances within cycling, with a particular focus on track cycling. For shorter distances such as the 400 m event, pacing is characterized by an initial sharp acceleration followed by a progressive decline in pace (Corbett, 2009; Craig & Norton, 2001). This phase is key to performance as a correlation was observed between the first lap time and final time for the top eight finishers in the 400 m event at the world championships (de Koning et al., 1999). Starting pace is also crucial for 3 km and 4 km individual pursuit events, although to a lesser extent (Corbett, 2009; Craig & Norton, 2001). These events are characterized by a more evenly paced profile, with the best performers better able to minimize any oscillations in power output (PO) that reflect positioning on the track (i.e., bends vs. straight sections; Craig & Norton, 2001). Therefore, research has effectively detailed the optimal pacing strategies across various exercise domains and distances. Now that we understand *what*, the next logical question to ask is *why*. Justifiably, explorations to better understand the regulation of endurance performance have long been theorized, with several important recent developments.

Models of Endurance Performance

Moving Beyond Catastrophe Models

Now referred to as ‘catastrophe’ or ‘peripheral’ models of exercise, seminal work proposed that fatigue develops when the heart is unable to produce a cardiac output sufficient to cover the exercising muscles’ increased demand for oxygen (Hill & Lupton, 1923). According to the researchers, this results in a state of skeletal muscle anaerobiosis, with lactic acid ‘poisoning’ the muscles and impairing their function. Hill and his team suggested that directly prior to exhaustion, whole-body oxygen consumption reaches a maximum value: the maximum oxygen consumption (VO_{2max}). However, more contemporary research has demonstrated VO_{2max} to be a poor predictor of athletic ability among cyclists (Lucía et al., 1998) and research has not demonstrated heart capacity (to transport and consume oxygen) to explain variance in athletic endurance ability (Billat et al., 2003). In addition, the model attributes no role to psychological factors in human endurance exercise performance. Building on this seminal research, Joyner and Coyle (2008) have provided an overview of the physiological characteristics that contribute to endurance performance. Specifically, they conclude that maximum oxygen consumption, lactate threshold and economy (or efficiency) are the key factors predicting endurance performance. However, the authors acknowledge that a complex interplay between motivational and social factors (e.g., competitor’s behaviour) further contributes to explaining differences in athletic performance. Hence, in the absence of accounting for these factors, no model can adequately explain decision-making processes involved in pacing.

There is mounting evidence to suggest that the above models cannot fully explain how endurance exercise is regulated. The most pertinent evidence relates to the catastrophe model premise that all available motor units must be recruited in active muscles at exhaustion. However, neurophysiologists have reached a consensus that a progressive reduction in force production during prolonged exercise is principally attributable to reduced central neural command (Gandevia, 2001). Moreover, as St. Clair Gibson and Noakes (2004) highlight, if peripheral models of fatigue are correct, what is the teleological value (i.e., natural purpose) of sensations of fatigue as exercise workload increases? Relatedly, such models are unable to account for the observed pacing strategies described above. Catastrophe models predict that fatigue progresses inexorably during prolonged exercise, with the highest fatigue experienced by athletes occurring directly prior to exhaustion. Were this premise true, athletes would be unable to increase their pace (e.g., PO) towards the end of a race to produce an ‘end spurt’ (Tucker et al., 2006). In sum, catastrophe models promote a concept of ‘brainless’ physiology (Noakes, 2008) and provide little scope for the function of the brain in the regulation of endurance exercise performance.

Research has also focussed on the role of consciousness in the self-regulation of endurance performance (Micklewright, Kegerreis et al., 2017). Early efforts to address this gap in knowledge proposed a dichotomous view, whereby minor homeostatic changes influence pacing behaviour at the unconscious or subconscious level, and larger homeostatic disturbances are consciously perceived and pacing behaviour is adjusted accordingly (Edwards & Polman, 2013). On the contrary, Micklewright, Kegerreis et al. (2017) believe this dichotomy is unhelpful, given that the unconscious has long been purported to give rise to subconscious and conscious states (Freud, 1900). This is evident in research highlighting organic shifts in attentional focus as a function of task duration or exercise intensity (Hutchinson & Tenenbaum, 2007). Here, attentional focus is directed to stimuli previously held in the subconscious, biased by interceptive cues during exercise. As a result, Micklewright, Kegerreis et al. (2017) proposed a dual-process approach to the quagmire of conscious influence over pacing. Through this lens, it is proposed that decisions are made under intuitive, automatic processes, or under deliberate, cognitively taxing executive control. Through both means, people develop heuristics (i.e., cognitive shortcuts) to selectively attend to what they perceive to be valuable information (when information is abundant) to simplify decision-making. Evidence to support this notion can be found in research demonstrating the influence of competitor behaviour on participant’s own pacing strategy (Williams et al., 2015). In addition, there is burgeoning evidence to support the role of executive function (i.e., goal-directed cognition), and therefore the processing of heuristics developed under deliberative means, being important in the self-regulation of endurance performance (Hyland-Monks et al., 2018). Hence, the dual-process approach can account for optimal and suboptimal performance determined by the usefulness of heuristics employed by an athlete.

Central Governor Model

In response to the lack of psychological representation within past models, the central governor model (CGM) was first proposed by Noakes and colleagues (Noakes, 2004, 2012a, 2012b). The ‘central governor’ subconsciously modulates motor unit recruitment based on a pacing strategy that functions to ensure that humans exercise in reserve and terminate exercise prior to catastrophic failure of homeostasis (e.g., myocardial ischemia resulting from insufficient blood flow to the heart). Afferent feedback (e.g., regarding metabolic rate and heat production) determines a subjective perception of fatigue that governs motor recruitment (i.e., a feedforward mechanism). Motor recruitment can be influenced by centrally acting modifiers, which encompasses “potentially everything” (Noakes, 2012b, p.6); thus, such modifiers could include pre-exercise biological status (e.g., mental or physical fatigue), cognitive and psychological factors (e.g., self-efficacy), and chemical agents (e.g., stimulants, such as caffeine). The model suggests that fatigue is a subjective sensation, analogous to an emotion, used to regulate exercise performance. Afferent feedback from numerous physiological systems is collated to determine a ‘conscious RPE’. This RPE is continuously compared to a subconscious ‘template’, which is developed to gauge the expected exertion to be experienced at given points during exercise of a known distance (often referred to as ‘end-point’ knowledge). Therefore, the regulation of exercise is determined by the adjustments of PO to minimise the discrepancies between actual and expected RPE, which is biologically linked to ensure homeostatic stability. More recently, the CGM has been adapted to incorporate the notion that high levels of motivation can ‘override’ the central governor (Evans et al., 2016). Although such situations may result in injuries, there are circumstances in which it would be evolutionarily adaptive to remove or modify the limits set by the central governor (e.g., in emergency fight or flight operations). Thus, in the context of exercise, a high level of motivation may allow the most committed of athletes to muster sufficient motivational levels to override the governor, risking serious illness or injury.

However, staunch critiques of the model, such as Inzlicht and Marcora (2016), highlight the difficulties the CGM faces in explaining fatigue and self-control failure. In seminal work, Baumeister et al. (2007) demonstrated that there is a ‘limited pool’ of self-control (i.e., the ability of the self to exert control over the self), which depletes with use, whether it be through physical or mental effort. This leads to a reduced capacity for further self-regulation: an effect termed ego-depletion. In a sporting context, self-control levels have been observed to decline over time during motor performance (i.e., repeated bouts of target shooting; Englert, Dziuba, Wolff, & Giboin, 2021). Glucose consumption is a key indicator of mental effort exerted; however, it is not considerably higher during the completion of effortful tasks, relative to the basal metabolic rate (Kurzban, 2010). Thus, if effortful mental tasks do not significantly deplete energy resources, what role does a central governor play in self-regulation, if self-regulation is to be partly determined by monitoring energy expenditure? In addition, if the ultimate function of the central governor is the maintenance of homeostasis, why is it so easily overridden? For instance, the use of motivational self-talk resulted in significant improvements in time-trial (TT) performance (Blanchfield et al., 2014). This seems to contradict the CGM, which suggests that such motivational override is exclusively reserved for the most extreme circumstances, such as high-stakes competition or life-threatening situations. Marcora (2009) has also collated evidence to suggest that afferent feedback from locomotor muscles is not a key determinant of endurance performance; one of the central tenants to the CGM. Pertinently, across several studies, a spinal blockade on III-IV receptors that are sensitive to fatigue-inducing metabolites did not reduce 5 km cycling TT performance (Amann et al., 2008, 2009). Considering this critique, Marcora (2010) has proposed the psychobiological model of endurance performance.

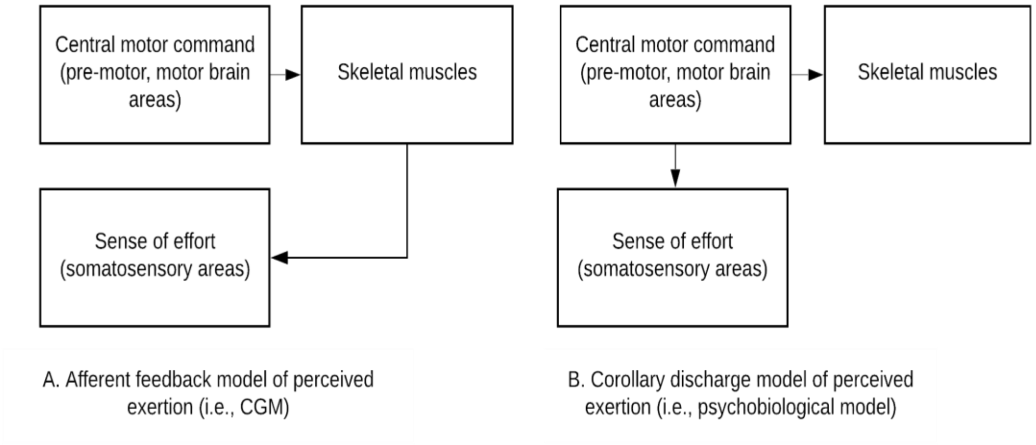
Psychobiological Model

According to Marcora (2010), the psychobiological model elucidates how the self-regulation of endurance performance is explainable in psychological terms, underlined by low-level neurobiological processes. The psychobiological model is an effort-based decision-making model and postulates that the conscious regulation of pace is determined primarily by effort perception and potential motivation. Effort perception is defined by a person’s perception of how strenuous physical activity is. Potential motivation is defined as the maximum amount of effort a person is willing to exert to succeed at a given task. Thus, in theory, any physiological or psychological manipulation that increases/decreases potential motivation and/or increases/decreases effort perception allows an individual to consciously regulate pace, ultimately helping to optimise their pacing strategy.

The adverse effects of mental fatigue on physical performance have been presented as evidence to support this theoretical premise. Mental fatigue has been defined as the prolonged effect of mental exertion on mood (e.g., sensations of tiredness, or a lack of energy) and/or performance of tasks requiring vigilance or other effortful cognitive processes (Boksem & Tops, 2008). Pertinently, the adverse effect of mental fatigue has been extended to the performance of physical endurance tasks, as summarised in Van Cutsem et al.'s (2017) review. Studies reviewed typically compared the effects of a prolonged and cognitively demanding task (e.g., the incongruent Stroop task) to a less demanding task (e.g., the congruent Stroop task) on subsequent endurance performance. Research has demonstrated a decrease in 5 km (Pageaux et al., 2014) and 3000 m running performance (MacMahon et al., 2014), a decrease in cycling PO at both light and hard intensities (Brownsberger et al., 2013), and a decrease in velocity achieved during intermittent running performance (Smith et al., 2015) under conditions of mental fatigue. Perception of effort was either higher under conditions of mental fatigue or unchanged for the same performance level. Inferring from the collated findings, Van Cutsem et al. (2017) suggest that perception of effort plays a significant mediating role in the negative effect of mental fatigue on physical endurance performance.

Despite sharing a role for psychology in the governance of pacing, the evidence base supporting the psychobiological model could be considered an antithesis for the basis of the CGM; the model postulates that effort perception is generated independently of afferent feedback from the locomotor muscles, heart, and lungs. Several studies have looked at effort perception and physiology during endurance exercise. For instance, research has shown that perception of effort was unchanged or increased during cycling exercise despite the use of a calcium channel β-adrenergic blockade to slow heart rate (Myers et al., 1987). It has been suggested that perception of effort is a ‘sensation of innervation’, in which corollary discharges from the central motor command are processed in the sensory areas of the brain (Marcora, 2009). Supporting this postulation, the dyspnoea experienced when exercising strongly reflects one’s sense of respiratory effort; this respiratory sensation is generated by corollary discharges of the central motor commands to the respiratory muscles (O’Donnell et al., 2007). Subsequently, evidence that perception of effort is generated in premotor and motor areas of the brain comes from research demonstrating simultaneous increases in effort perception, electromyogram, and movement-related cortical potential amplitudes as weight lifted and fatigue increased during the performance of dynamic elbow flexions (de Morree et al., 2012). Although, it should be noted that a dynamic elbow flexion protocol is likely to have different physiological, neuromuscular, and neuropsychological effects than whole-body dynamic exercise, such as running. Figure 1.3 highlights the key differences between the CGM and psychobiological model with respect to how effort perception influences the self-regulation of endurance performance.

Figure 1.3 A Schematic Diagram of the Afferent Feedback (A) Versus Corollary Discharge (B) Model.



Note. Reused with permission from Marcora (2009).

Finally, a criticism of the CGM and the psychobiological model is their overreliance on the concept of perceived exertion or effort, which has become a topic for debate on conceptual and methodological grounds (Halperin & Emanuel, 2020). This is demonstrated by the measurement and interpretation of RPE being confounded by the interchangeable use of ‘effort’ and ‘exertion’, which are distinct but interrelated concepts (Abbiss et al., 2015). Promisingly, attempts have been made to isolate perceived physical symptoms by adapting the RPE scale to only reflect physical strain, and the development of a new scale to assess mental sense of effort exclusively: the task effort and awareness scale (Swart et al., 2012). Cyclists could differentiate between the two scales during submaximal workloads, but not during time to exhaustion tests and full-effort TT’s. This suggests that perceived physical and mental strain can be experimentally dissociated.

Recently, Venhorst and colleagues (Venhorst et al., 2018) have proposed a three-dimensional framework to combat the critique of oversimplification in the proposed models above. Firstly, perceived physical and mental strain are the salient regulators or pacing behaviour, and are necessary to align behaviour with goals and intentions (e.g., pre-race strategy). Core affect (i.e., valence and arousal) is proposed to play a mediatory role. A notable adjunct here is the dual-mode hypothesis, which postulates that a change from a positive to negative affective state occurs around the ventilatory threshold (Ekkekakis, 2005), a point at which executive control of affect is predominated by the salience of physiological feedback. Lastly, cognitive flexibility is required in 'action crisis' (e.g., being unable to maintain the pace of opponents), driven by a psycho-neuroendocrinological distress response, to self-regulate pace when race goals need to be recalculated.

Cognition and Endurance Performance

Cognition, Thought Processes and Think Aloud

Given the increasing integration of psychology into models of endurance performance, recent research has begun to investigate the nuance of cognitive processes that underlie the governance of pacing. Brick, MacIntyre, and Campbell (2016) argue that the dual-mechanisms of control framework (Braver et al., 2007) is a useful prism by which to assess the cognitive processes involved in pacing. The framework postulates that there are two modes of cognitive control: proactive and reactive control. Proactive control involves the goal-directed processing of information so that attention, perception (e.g., RPE), and action (e.g., maintaining pace) are biased favourably toward goal obtainment. Reactive control is automatic and transient, and only engaged when required (e.g., to adjust PO to catch a competitor). Relative to proactive control, reactive control is less demanding of cognitive resources (e.g., executive functions). Following on, according to Brick, Campbell et al. (2016), metacognitive skills (i.e., planning and monitoring) and experiences (i.e., feelings and judgments) are key to the self-regulation of endurance performance. Planning may incorporate goal setting and strategizing, such as establishing a pacing profile to follow (e.g., split times to aim for), and selection of a psychological intervention to use during a race (e.g., motivational self-talk). Monitoring could involve athletes developing a means of prioritizing sensory information (e.g., noticing an opponent tiring) to optimize performance (e.g., increasing the pace to overtake an opponent). In addition, internal (e.g., pain in the legs) and external (e.g., competitors' whereabouts) stimuli generate implicit and explicit metacognitive feelings (e.g., pace feels quick and easy). Where conscious, these feelings can inform an athlete's representation of the task at hand (e.g., the pace is too slow) which can aid decision-making (e.g., increase the pace to distance opponents). An athlete can then metacognitively appraise the decision (e.g., opponent successfully distanced, so maintain pace). The notions above form part of the broader metacognitive framework of attentional focus and cognitive control for exercise self-regulation (Brick et al., 2014), covered in further detail in subsequent chapters.

Brick and colleagues (Brick, Campbell et al., 2016) have experimentally tested their proposed framework. During a 3 km run, participants reported cognitive strategies that were suggestive of reactive (e.g., a focus on pacing and subsequent adjustments) and proactive (e.g., 'chunking' or segmenting of the race) forms of control. When the pace was externally controlled using a representation of previous performance, strategies adopted (e.g., relaxation and optimizing form) indicated that participants predominately utilized reactive control. This was coupled with a 2% decrease in heart rate (an indication of greater economy). These observations were taken as a reflection of the difference in cognitive strategies adopted, and thus a reduced engagement of executive function by participants. Notably, there is overlap between the dual-mechanism concept of proactive and reactive control proposed here, and deliberate and automatic processes proposed by Micklewright and colleagues above (Micklewright, Kegerreis et al., 2017). More recently, Brick et al. (2019) tasked trained runners with completing a 3000 m treadmill run with both a 'known incline' (KI), where the last 800 m was completed at a 7% gradient, and an 'unknown incline' (UI), which was completed under the same conditions but participants were unaware of the gradient change. Relative speed was slower between 200-2200 m in the KI than UI trial, resulting in a slower performance by 14 seconds at the 2200 m mark. Subjects focussed more on pacing at the 1000 and 2000 m marks in the KI compared to UI trial. In addition, in the final 800 m, motivational thoughts were more prevalent in UI relative to the KI trial; relaxation and 'chunking' techniques were used more in the KI than UI trial. Therefore, a greater focus on pacing is required when a conservation of energy is salient (i.e., KI), and self-regulatory techniques (e.g., motivational self-talk) are utilised more when confronted with an unexpected challenge (i.e., UI). Here, evidence is presented that demonstrates how prior and in-event planning and monitoring of pacing behaviour is influenced by anticipated task difficulty, alongside judgments and expected feelings of completing a flat versus unexpectedly hilly finish to a running challenge.

In both studies highlighted above, participants were asked to recall their thought processes retrospectively, albeit with the aid of cues (which itself could be considered a problem of bias). Such retrospective methods are subject to several limitations, most notably inaccurate or unreliable recall (Nicholls et al., 2008). Research within sport has recently begun to explore methodologies that circumnavigate this problem. There is a burgeoning field of research that has adopted the think aloud (TA) protocol to capture the thought processes of those completing endurance activities (Massey et al., 2020; Samson et al., 2017; Whitehead et al., 2017, 2018). Briefly, TA involves verbalizing thoughts as they are experienced during task performance: concurrent reporting (Eccles & Arsal, 2017). Using TA, in both field and laboratory experiments, researchers have begun to investigate how the thought processes of endurance performers relate to physiological parameters, trained status (i.e., expert vs. novice comparisons) and task dynamics (e.g., stage of the race). Moreover, using TA, research has explored the thought processes of endurance performers concerning the metacognitive processes described above. As TA will form the methodological backbone of the next chapter, it would be prudent to assess its usefulness in achieving the above. This caution is warranted as interference (i.e., reactivity) effects from using TA on the primary task at hand have been observed in other domains (Fox et al., 2011), but discussion of these effects in sports performance settings is limited.

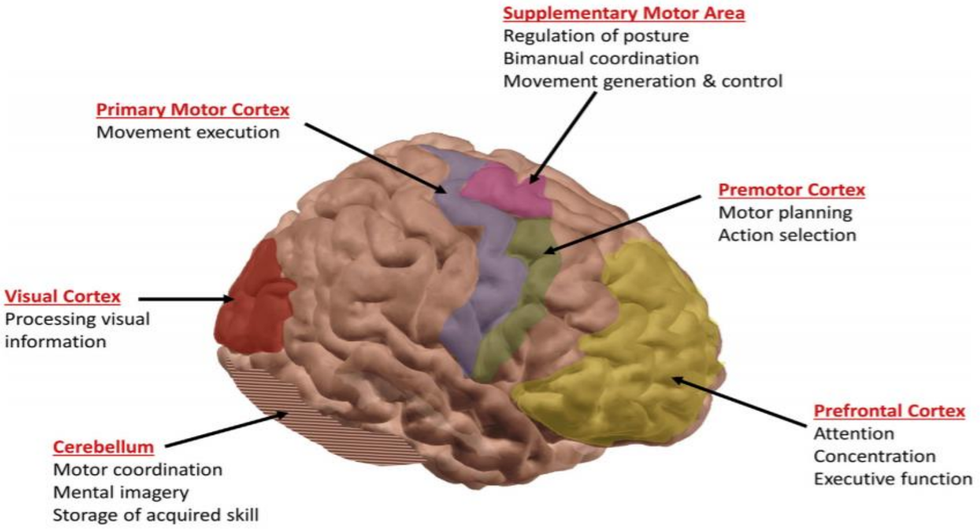
In building on the work above, the research featured in Chapter 2 will converge on an overarching aim: What does the verbalisation of thoughts, captured via TA, contribute to our understanding of the self-regulation of pacing? This aim can only be achieved if TA does not compromise endurance performance, which will be subject to investigation. Moreover, this aim can only be realised if we accept that conscious verbalisation of thinking is sufficiently representative of attentional focus, cognition and thought processes occurring ‘in the moment’, which will also be discussed.

The Prefrontal Cortex, Executive Function and Functional Near-Infrared Spectroscopy (fNIRS)

In parallel to the research presented above, neuropsychological research is shedding light on the important brain structures involved in aerobic exercise regulation. The prefrontal cortex (PFC) is of particular interest, which is implicated in executive function: defined as a top-down regulation of ‘lower-level’ cognitive processes to aid goal-directed behaviour (Alvarez & Emory, 2006). Cerebral activity of the PFC has been measured via functional near-infrared spectroscopy (fNIRS), which is a non-invasive technology used to measure the absorption spectra of oxyhaemoglobin and deoxyhaemoglobin (Villringer et al., 1993). Greater detail on fNIRS will be provided in the coming chapters. A review into the relationship between incremental exercise and cerebral oxygenation, as measured by fNIRS, highlighted that PFC activity changes as a function of exercise following a quadratic trend (Rooks et al., 2010). PFC oxygenation increases at low-to-moderate intensities and stabilised at moderate-to-hard intensities, before declining at near maximal and exhaustive intensities.

The reticular activating hypofrontality (RAH) model (Dietrich & Audiffren, 2011) postulates specific neurological phenomena concerning PFC activity during exercise. The model works on the premise that whole-body dynamic exercise is metabolically costly, and neural processing, requiring the brain’s limited metabolic resources, continually occurs on a competitive basis. As a result, there is a compensatory transient downregulation in brain areas involved in higher-order cognition (i.e., the PFC) to brain regions more important for the control of movement during exercise: motor, sensory and autonomic areas (Figure 1.4.). In addition, the greater the duration, and to a lesser extent, intensity of exercise, the greater the hypofrontality effect. Due to this hypofrontality, the model predicts that cognitive processes (i.e., top-down, goal-driven processes) will be compromised during exercise, and therefore the self-regulatory processes that are key to pacing. The strongest neurological evidence to date comes from animal studies demonstrating a hypofrontality effect during exercise. An increase in local glucose substrate utilization was found for all but a few select brain areas, including the PFC, when rats exercised for 30 minutes on a treadmill at 85% maximum oxygen uptake (Vissing et al., 1996). Although similar work in humans is not possible due to ethical and practical reasons, both electroencephalogram (EEG, e.g., Nybo & Nielsen, 2001) and fNIRS (Thomas & Stephane, 2007) methods have indicated patterns of deactivation in prefrontal areas during aerobic exercise in line with workload intensity. In further support of the model, Dietrich and Audiffren (2011) collated research that demonstrates an impairment to prefrontal-dependent cognition, but not general cognitive processes, as a result of exercise.

Figure 1.4 The Cerebral Cortex.



Note. Reused with permission from Modi et al. (2017).

However, research to date has predominately focussed on evolutionary perspectives (Dietrich & Audiffren, 2011) and how this may relate to hedonic tone (Ekkekakis, 2009). Little research has bridged the gap between neuropsychology and the self-regulation of *self-paced* endurance activities, and therefore the importance of executive function to endurance performance. For instance, faster ultra-marathon runners (i.e., those with faster finishing times) demonstrated superior executive function than slower runners (Cona et al., 2015). Research has also demonstrated that the mental fatigue effects described above (induced by prolonged prefrontal dependent testing) impacted TT performance more in professional cyclists versus recreationally active controls (Martin et al., 2016). In addition, research has observed fNIRS parameters to be strongly correlated with cycling PO in TT performance (Wingfield et al., 2018). This research suggests that there is a relationship between the PFC, executive function and endurance performance, possibly through the metacognitive processes highlighted above. This evidence base will be detailed further in subsequent chapters, alongside the role of the PFC and executive function in endurance performance. Lastly, it is important to note that much of the evidence presented above is collated using the aforementioned fNIRS technology. This type of neuroimaging is a relatively recent development in sports science, with potential issues around movement artefacts during exercise (Herold et al., 2018). Therefore, as with TA above, it would be prudent to investigate how confident we can be in exercise-based research findings derived via fNIRS.

The second overarching aim of this thesis is to investigate the neurocognitive underpinnings of the self-regulation of endurance performance. Chapter 3 will gather evidence from studies measuring cognition and PFC activity to investigate their contribution to pacing behaviour. Furthermore, to achieve this aim, it is important to establish the feasibility of measuring PFC activity by fNIRS during self-paced performance, which will be subject to inquiry in Chapter 4. Following on, with effective use of fNIRS, Chapter 5 will provide an example of how fNIRS can be used to investigate the function of the PFC in self-regulating cycling performance.

Self-Regulation in Real-World Exercise Settings

Given the limitations placed on research practices related to the pandemic from March 2020, planned laboratory work was no longer an option for the foreseeable future. As such, data collection for the research presented in Chapter 5 was halted. Therefore, a case study is detailed as opposed to a full experiment, as initially intended. However, these changes also provided an opportunity to conduct a different type of research, away from the labs and in the field, taking advantage of endurance performer’s natural training routines. Although this work would take a more exploratory approach, in contrast to the more experimental work presented beforehand, it has the advantage of more accurately capturing performer’s psychology in real-life exercise settings. Moreover, it allowed the researcher to take a ‘step back’ to observe how variables of interest interact in the real-world to inform more finely tuned investigations to follow (Bishop, 2008).

Previous chapters outline how self-regulatory processes are key to the decision-making and pacing of endurance performance (Hyland-Monks et al., 2018, i.e., Chapter 3). Through these chapters, it is argued that prefrontal areas are in part responsible for the top-down executive control of pacing behaviour (Hyland-Monks et al., 2018, 2022) and exercise tolerance (Robertson & Marino, 2016). Although this work has addressed executive functions and synonymously, metacognitive processes (Brick, MacIntyre, & Campbell, 2016), little attention has been paid to self-control capacities and their impact on endurance performance regulation.

As previous highlighted, resource-based models of self-control (Baumeister, 2002) centre around the notion that self-control resources are limited and can be depleted with use. State self-control has been shown to deplete over time in line with motor performance (Englert, Dziuba, Wolff, & Giboin, 2021), with elite athletes appearing better able to stave off these effects over time (Englert, Dziuba, Giboin, & Wolff). However, to date, no such measures have been used in earnest to assess self-control among endurance performers. It would seem plausible that the unique demands of endurance sport would be demanding of self-control resources. For instance, the need for proactive and reactive control (Brick, MacIntyre, & Campbell, 2016) to continually pace effort using performance feedback, whilst also reacting to opponent's behaviour. This places a heavy demand on attentional resources (Brick et al., 2014), with boredom-inducing long-distance exercise linked to aversive experiences in competition (Weich et al., 2022), and a high prevalence of mind-wandering reported among endurance athletes (Latinjak, 2018). Therefore, self-control losses could have deleterious effects on performance.

As a result, the final overarching aim of the thesis is to capture the self-regulatory processes contributing to endurance performance and pacing within performer's natural training routines. Moreover, to investigate how self-control resources impact attentional control and affective responses related to exercise.

Summary

In summary, there is a continued and burgeoning interest in understanding endurance performance across sport science. Pertinently, theories developed to understand pacing phenomena have begun to centre around psychological factors. This research has taken neuropsychological and cognitive approaches, which involve the importance of metacognitive processes and the top-down self-regulation of pacing from the PFC. Adopting TA and fNIRS methodologies, this thesis will attempt to establish what people say (and can consciously verbalise), and what brain activity (a subconscious reflection of active regions) can reveal about the self-regulation of endurance performance. Given the relative novelty of these methodologies to endurance performance research, the feasibility of these methods will also be investigated. Lastly, a ‘step back’ will be taken to explore the contribution of self-regulatory processes to endurance performer’s perceptual experiences in training.

Chapter 2 Using Think Aloud to Investigate the Relationships Between Cognition, Psychophysiology, and Self-Paced Cycling Time-Trial Performance: A Methodology Examination

Abstract

Think aloud (TA) has been used to capture cyclist's thought processes during time-trial performance, however, the feasibility of using TA in such settings has not been empirically investigated. Therefore, this research aimed to investigate the impact of TA on cycling time-trial performance (i.e., reactivity). It was predicted that using TA would negatively impact performance. The research also sought to investigate the associations between thought processes, cognition, psychophysiology, and cycling performance to better understand the psychology of pacing behaviour. Eight endurance trained cyclists and eight non-endurance but physically active participants completed a 16 km baseline, No TA, and TA cycling time-trial. Perceived exertion and affect were measured during, and cognitive functioning (i.e., flanker task) before and after trials. Saliently, no difference in finish time was found between the TA and No TA conditions ($p = .72$, $\eta p^2 = .010$), suggesting that TA does not adversely affect endurance performance. However, flanker task performance was slower after the TA versus No TA time-trial, but not significantly. Interoceptive and self-regulatory verbalizations increased, whilst distraction-related verbalizations decreased as the time-trial progressed. This possibly reflects an external-to-internal shift in attention and subsequent self-regulatory efforts. This is reinforced by greater distraction-related verbalizations in a positive versus negative affective state. Power output verbalizations were significantly higher for trained cyclists versus their non-trained counterparts. Methodological, theoretical, and applied implications are discussed.

Introduction

Think aloud (TA) involves verbalizing thoughts as they are experienced during task performance (Eccles & Arsal, 2017). It is suggested that verbalizations reflect at least a subset of thoughts encoded in short-term memory concerning task performance (Ericsson & Simon, 1980). This 'heeded' information is commensurate with level 1 and 2 verbalization, with the salient difference being the simple verbalization of inner speech (level 1), as opposed to the vocalisation of inner thought processes (level 2). Anything beyond this (e.g., reflective processes) is considered level 3 verbalization.

TA has recently been used to capture thought processes during endurance exercise activities (Massey et al., 2020; Samson et al., 2017; Whitehead et al., 2017, 2018). Seminal fieldwork by Samson et al. (2017) instructed runners to use TA for a self-paced outdoor run. Thoughts regarding pacing and discomfort were most frequent, and coping strategies were adopted to maintain pace and manage pain. Thoughts relating to the environment were speculated to function as a distraction from discomfort. A further study by Whitehead et al. (2017) asked club-level cyclists to use TA during a full-effort 16.1 km outdoor time-trial (TT). Fatigue and pain verbalizations were more frequent in the early stages of the TT, whereas distance verbalizations increased significantly in the final stages. These trends may relate to ineffective pacing at the start and the need to regulate pace in the closing stages to avoid premature failure (St. Clair Gibson et al., 2013). More thoughts were verbalized in the first than the last quartile, possibly reflecting greater task uncertainty and complexity in the early stages. Alternatively, research has yet to explore whether this may indicate the cognitive challenge of self-regulating effort and thinking aloud simultaneously as exertion levels rise.

Whitehead et al. (2018) investigated the relationship between thought processes and performance feedback (e.g., power output, PO) during a laboratory-based 16.1 km TT. Thoughts captured were categorised into themes per Brick, MacIntyre and Campbell's (2016) metacognitive framework of endurance performance: internal sensory monitoring, active self-regulation, outward monitoring, and distraction. Cyclist's thoughts predominantly related to active self-regulation and distraction (over 80% of total verbalizations). Motivational statements were significantly higher in the final quartile, coinciding with increased PO.

Whitehead et al. (2018) also found trained participant's thoughts were significantly more self-regulatory and distance-related, suggesting that trained participants reactively used such sources of information to gauge effort and optimise pacing. In contrast, untrained participants verbalized more thoughts regarding distraction and pain, which coincided with a decrease in pace in the second and third quartiles following a faster first quartile. This was possibly a result of sub-optimal pacing, with participants exceeding their ventilatory threshold (occurring between 50-75% VO_{2max}), leading to a negative affective state (Ekkekakis et al., 2011).

According to the reticular activating hypofrontality (RAH) model (Dietrich & Audiffren, 2011), this change in affective state is reflective of certain cortical changes during exercise, chiefly a transient downregulation (i.e., hypofrontality) in the prefrontal cortex (PFC), involved in higher-order cognition (i.e., executive function), to regions more important for movement control. As highlighted in a recent review, such cortical perturbations may impact a performer's capacity to effectively use top-down goal-directed cognition to optimize their pacing (Hyland-Monks et al., 2018). Relatedly, research has observed a shift from a voluntary dissociative focus (e.g., on environmental stimuli) during low-intensity (50% VO_{2max}) cycling exercise, to an associative focus (e.g., on bodily sensations) during high-intensity (90% VO_{2max}) cycling exercise (Hutchinson & Tenenbaum, 2007). This could have important implications for attentional control and therefore performance during exercise (Wulf & Lewthwaite, 2016).

Massey et al. (2020) combined TA with eye-tracking during a 16.1 km cycling TT. Trained participants verbalized more internal sensory monitoring- and PO-related thoughts, whereas untrained participants verbalized more content overall, and more thoughts concerning scenery (i.e., the virtual cycling simulation), time, and distance, indicating a greater task focus among trained cyclists. Visual dwell time was dominated by scenery and PO fixations. Gaze behaviour beyond areas of interest was screened out of the analysis but could be explainable by a voluntary or involuntary focus on 'off-task' stimuli. The dwell time on PO in the untrained participants is particularly notable, as this is not reflected in the TA data. This suggests that gaze behaviour may not always constitute conscious thought processes and perhaps represents a threshold of information that is not verbalized from visual stimuli input. This could relate to subliminal heuristics developed to select the information salient to the individual (Haberman & Whitney, 2011).

TA appears to be a viable method for measuring concurrent thought processes during endurance exercise. However, existing research has yet to quantitatively investigate the prospect of TA interfering with the performance of the primary task: referred to as *reactivity* (Fox et al., 2011). More specifically, the challenge presented to participants of engaging with level 2 TA verbalization while partaking in full-effort endurance performance. A meta-analysis by Fox et al. (2011) demonstrated that when used appropriately, TA should not interfere with task performance but tends to increase task completion time. If reactivity does occur, future work may have to account for this when time is used as a measure of task performance. In Whitehead et al.’s (2018) research, participants reported that the strenuous nature of the exercise made verbalizing thoughts challenging, believing that TA negatively affected their performance. Based on these accounts, it is perhaps worth considering how exercise impacts TA, particularly when one considers the possibility of hypofrontality during high-intensity exercise (Dietrich & Audiffren, 2011). Therefore, this is a pertinent area for exploration as completion time is a crucial element of endurance sports (e.g., TT races).

Pertinently, recent experimental work has compared TA versus no TA conditions during self-paced steady-state exercise, ranging from light to maximal effort (Whitehead et al., 2022). Physiological markers and PFC haemodynamics were measured during exercise. Heart rate, blood lactate and rating of perceived exertion (RPE) were lower during TA conditions, providing tentative evidence that TA may benefit self-regulatory efforts. However, little difference in cortical haemodynamics were observed to suggest any clear effects of TA on brain activity. Although beyond the remit of Whitehead et al.'s (2022) research aims, the impact of high-intensity exercise on the quality of TA content remains unexplored.

Several psychological factors could account for TA reactivity during endurance exercise performance. Conscious reporting of thought processes may facilitate an internal focus (e.g., on physiological sensations) that potentially constrains motor performance such as pedalling efficiency (Schücker et al., 2016). Therefore, reactivity could depend on how TA influences one’s attention during exercise performance. Moreover, the cognitive demand of TA could induce mental fatigue, shown to negatively impact physical performance (Van Cutsem et al., 2017). Reactivity may also be subject to level of expertise, with TA during golf putting resulting in no reinvestment (i.e., explicit monitoring of skill execution) among skilled performers (Whitehead et al., 2015), for whom skill execution was likely automated (Beilock et al., 2002). However, endurance performance tasks have yet to be subject to such investigations.

As such, this study aims to investigate the impact of TA on endurance performance and vice versa, alongside what factors (e.g., cognitive load) may explain this relationship (i.e., TA *feasibility* analysis). Given that reactivity has been observed in response to the completion of tasks while using TA (Fox et al., 2011), it was hypothesised that using TA would negatively affect TT performance (i.e., slower completion time and lower PO). Moreover, it was predicted that reactivity may also be evident in psychophysical perceptions (i.e., higher RPE and perceived fatigue, and lower affective state) and cognitive performance post-exercise (i.e., slower response time and lower accuracy). In turn, considering the impact of exercise on TA, it was predicted that the prevalence of TA content (i.e., verbalizations) would be greater in the early compared to latter stages of the TT (i.e., in the last vs. first quartile of the TT).

Furthermore, this study aims to provide fresh insight into the relationship between thought processes, psychophysiology, and cognition during endurance performance. The study findings will be discussed in relation to contemporary thinking regarding the self-regulation of endurance performance (i.e., TA *content* analysis). As an extension of recent research on TA and cycling performance (Massey et al., 2020; Whitehead et al., 2017, 2018), it was hypothesised that self-regulatory verbalizations would predominate, and motivation and distance-related verbalizations would increase in the final quartile. It was also predicted that trained persons would verbalize more self-regulatory and performance-related thoughts than their counterparts, who would verbalize more distraction-related thoughts. Following on, it was hypothesised that verbalizations would reflect increasing workload and affective valance associated with cerebral changes during exercise (Dietrich & Audiffren, 2011). Therefore, thoughts were predicted to shift from an external (e.g., on scenery) to an internal focus (e.g., on pain) across the TT (i.e., in the first vs. last quartile of the TT). Moreover, that thoughts would reflect affective state and therefore feature more internal foci when negative, and more external foci when positive.

Method

Participants

As small sample sizes have created difficulties in generalising findings to target populations in sports psychology research (Schweizer & Furley, 2016), a power analysis was conducted for the key hypothesis under investigation. Therefore, with reactivity being the key outcome measure, an effect size was calculated based on the findings observed by Fox et al. (2011) for task reactivity (i.e., slowed response times) when using TA ($r = .31$). An *a priori* power analysis was performed in G*Power3 (Faul et al., 2007) to determine a minimum sample size to detect TA reactivity in TT performance, revealing a required $n = 16$ ($1-\beta = .80$, $\alpha = .05$). Therefore, the study recruited 8 'endurance trained' (ET) (7 male) and 8 'non-endurance trained' (Non-ET) but physically active participants (all male) to take part in this study. Additionally, this sample size is commensurate with similar research (Massey et al., 2020; Samson et al., 2017; Whitehead et al., 2017, 2018). Endurance trained participants were recruited by approaching local cycling clubs and teams, and Non-ET participants were recruited by circulating a study advertisement to university staff and students. Endurance trained participants met De Pauw et al.'s (2013) criteria for 'level 3' indicators of 'cycling status': 1) Train at least 3 times a week, for a total of at least 5 hours, and cover at least 60 km; and 2) Have competitive experience in cycling. Non-endurance trained participants were not regular cyclists but met the recommended ≥ 150 minutes of physical activity per week according to the American College of Sports Medicine (Garber et al., 2011). Therefore, the key difference between the groups was their experience in pacing and self-regulating effort concerning endurance performance. All participants were White European and university educated. No significant differences were found between groups for age, weight, height, body fat percentage, and body mass index (all $p > .05$; see Table 2.1). However, ET participants reported exercising for significantly longer per week (hrs) than Non-ET participants, $M_{\text{difference}} = 3.00$, $t(14) = 2.65$, $p = .019$. All participants were subject to health screening and provided written informed consent. Participants were debriefed following their last visit and provided with the opportunity to ask any questions. Ethical approval was granted by the university research ethics committee. Data collection ran from June 2018 to December 2020 and was conducted in the physiology laboratory of the host institution.

Table 2.1 Mean (*SD*) Anthropometric Data and Physical Activity Levels by Trained Status.

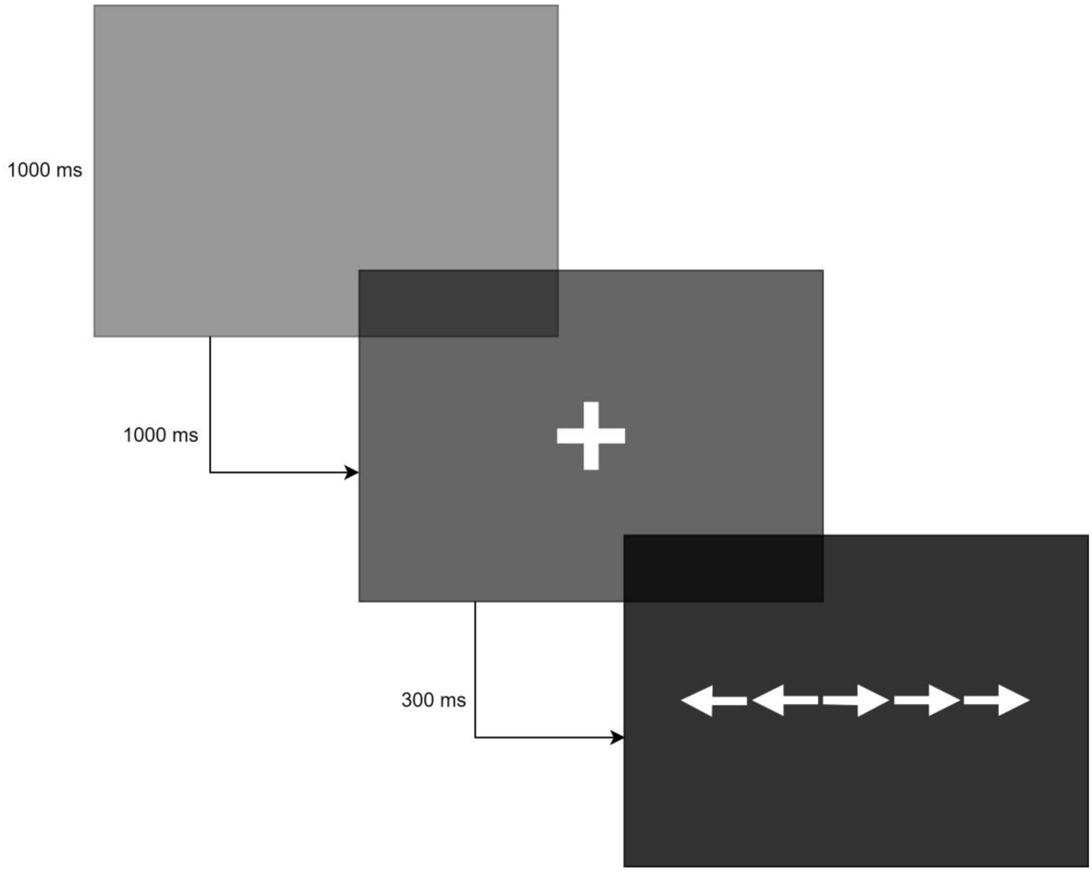
Participant characteristics	**Non-ET (*n* = 8)**	**ET (*n* = 8)**
Age (years)	38.38 (16.73)	35.00 (8.77)
Body weight (kg)	77.37 (7.21)	75.25 (9.57)
Height (cm)	178.00 (4.69)	177.88 (8.63)
Body Mass Index (kg/m^2)	24.55 (2.22)	23.70 (1.94)
Body fat percentage (%)	15.33 (6.23)	14.01 (7.67)
Weekly physical activity (hours)[a]	7.00 (1.93)	10.00* (2.56)

Note. ET = endurance trained, Non-ET = non-endurance trained.
[a]Includes all forms of physical activity.
*Significant group difference $p < .05$.

Materials and Measures

Pre- and post-task measures. An Eriksen Flanker Task was devised by the researcher in E-Prime (Psychology Software Tools: Sharpsburg, USA) and used to capture the effects of TA on cognition. The flanker task reflects inhibitory executive function at the neuropsychological level (Heil et al., 2000) and has been successfully used in exercise-based research (Davranche et al., 2009). Response inhibition is thought to be key to exercise tolerance (Robertson & Marino, 2016) and has been shown to explain differences between the capabilities of endurance athletes (Cona et al., 2015). Hence, if TA use impacts cortical demands relevant to endurance effort, this may be reflected in response inhibition performance. Visual stimuli consisted of white arrows and squares presented on a black background. Participants are instructed to indicate which direction the centre arrow is facing as quickly and accurately as possible by pressing a keyboard button for left (‘D’) or right (‘K’). Three conditions representing different distracting stimuli are presented on either side of the centre arrow: congruent trials (centre arrow and distractor arrows are aligned in direction; ←←←←←), incongruent trials (centre arrow faces in the opposite direction to distractor arrows; ←←→←←), and neutral trials (white squares presented either side of centre arrow; ■ ■ ← ■ ■). Over 120 trials all stimuli are presented equally in a randomised order. Before stimuli are presented, a blank screen is shown for 1000 ms, followed by a priming fixation point for 1000 ms. Stimuli are then presented for 300 ms regardless of response time. Twenty practice trials are completed before the test commenced. To best capture response inhibition, calculating the interference score (incongruent minus congruent performance) is recommended (Tillman & Wiens, 2011) and will be the dependent variable for both accuracy and reaction time (RT) data. A trial sequence for an incongruent trial is presented in Figure 2.1. Self-reported fatigue was assessed via the Rating of Fatigue (ROF) scale (Micklewright, St. Clair Gibson et al., 2017).

Figure 2.1 A Flanker Task Trial Sequence for Incongruent Stimuli



In-task measures. To measure TT performance, the Racermate software and electromagnetically-braked Velotron cycle ergometer (Racermate: Seattle, USA) were used to simulate a virtual flat 16 km cycling TT. A 16 km TT is a demonstrably reliable performance criterion for trained cyclists (Sparks et al., 2016). Alongside a projection of the virtual TT course, including an avatar that represents the participant, distance covered (km), speed (km.hr^{-1}), PO in watts (W), cadence (r.min^{-1}), and gearing were provided as real-time feedback along the bottom of the screen (see Item 1, supplementary materials for visual display). Time elapsed and TT completion time were obscured from participants to avoid the potential for comparison of times. In line with previous work (Swart et al., 2008), the software-generated ‘SpinScan’ score (average torque/maximum torque x 100) was used to assess pedal stroke dynamics. The bike was positioned centrally 1.5 m apart from a 100 cm (height) x 180 cm (width) screen projection of the virtual environment. The 15-point Borg Scale (Borg, 1982) was used to measure rating of perceived exertion (RPE). To measure affect, the Feeling Scale (Hardy & Rejeski, 1989) was used. Participants wore a Garmin Forerunner 15 watch and chest strap (Garmin: Kansas, USA) to monitor heart rate (bpm), which was visible to participants as feedback. In the TA condition, verbalizations were recorded via a dictaphone.

Experimental Protocol

Visit 1. Firstly, participants were provided with a descriptive overview of TA verbatim and were then required to complete three practice exercises adapted from Samson et al. (2017) to assess participant’s comprehension of TA (see Item 2, supplementary materials for TA description and practice exercises). Participants were also encouraged to practice TA during one exercise bout prior to the experiment. Participants were asked to wear light athletic clothing and abstain from alcohol and vigorous exercise 24 hours before participation. The TT’s were completed at the same time of day (± 1 hour) in the same laboratory regulated to 21 °C (± 1 °C). Directly before the TT’s, participants completed the cognitive testing and ROF assessment. A 5-minute warm-up at 40% of the participant’s heart rate reserve was completed before each TT. Participants then completed a baseline familiarisation full-effort 16 km TT. Affect and RPE were recorded from participants every 2 km’s for each TT. Directly after the TT’s, participants completed the cognitive test and ROF scale again before commencing with a cool-down that was equivalent to the warm-up.

Visits 2 and 3. Participants completed a full-effort 16 km TT on two further counterbalanced occasions, between two days and a week apart: once while adopting TA (TA condition) and once when not using TA (No TA condition). The procedure for the TT’s was the same as described for visit 1. Before commencing the TA TT, the researcher reiterated the key instruction to “please think aloud, and try and verbally express anything that comes into your head throughout the trial”. A visual reminder stating “please think aloud” was placed above the display screen. Participants were also asked to TA during the warm-up. To minimise disruption, distracting stimuli were removed from the environment and the researcher was out of sight of the participant when not required.

Data Analysis

TA feasibility. All inferential statistical testing was completed in SPSS (v.25). In line with established guidelines (Field, 2013), normality was analysed by visual inspection of distribution, skewness and kurtosis z scores, and Shapiro-Wilk statistics. Where relevant, TT finish time (secs), watts per kilogram (w/kg), cadence, SpinScan, affect, RPE, ROF, and flanker task data were analysed across trial (TA vs. No TA trials), trial split (4 quartiles), session (pre- vs. post-trial), and group (ET vs. Non-ET). ANOVAs were conducted for the above analyses and Greenhouse-Geisser corrections were applied for violations of sphericity assumptions. To account for the effect of TA prevalence on performance, ANCOVAs with transcribed word count as a covariate were performed for the above analyses that included trial comparisons, with appropriate additional assumption checks performed (i.e., homogeneity of regression slopes). Statistical significance was accepted at the probability criterion of $p < .05$. *Post hoc* pairwise comparisons with Bonferroni-adjusted p values were conducted for significant F-ratios. Partial eta squared (ηp^2) is reported for main effects and interactions, and Cohen’s d was calculated as appropriate to the research design (Lakens, 2013) and reported for *post hoc* pairwise comparisons. For conciseness and importance to the analysis, only 2-way interactions including trial comparisons were reported. All unreported interactions were non-significant ($p > .05$).

TA content. A post-positivist approach informed the data analysis process, whereby observations were analysed to test the propositions of extant theories. Using NVivo (v.11, QSR International Pty Ltd, 2015), deductive content analysis was performed on the transcribed TA data. This allowed for the identification of meaningful ‘units’ to be sorted into preconceived primary and secondary themes aligned with Brick, MacIntyre and Campbell’s (2016) metacognitive framework (see Table 2.2), as performed in previous similar research (Whitehead et al., 2017, 2018). Abductive reasoning was also performed to generate several new secondary themes to best categorise unsorted data within the framework (denoted in Table 2.2).

Therefore, this reasoning is merely a ‘fair guess’ in the presence of novel circumstances (Lipscomb, 2012). A list of definitions for each code (i.e., secondary themes) was produced to aid the sorting process (featured in Table 2.2) that was completed twice by the primary researcher to ensure methodological rigour. Given the concerns regarding a coder’s subjectivities and histories confounding reliability testing (Smith & McGannon, 2018), McAlister et al.'s (2017) recommendations to ensure inter-coder reliability were followed. Two independent researchers coded one participant’s transcribed TA data selected at random, which constituted 17% of TA data. The coding list with examples and definitions was provided to all parties and coders were tasked with tabularizing the assignment of codes with the corresponding data. Agreements and disagreements were then tallied per code and inter-rater reliability was determined by calculating percentage agreement between coders both ways to account for differences in total codes assigned. This resulted in an aggregated 89% agreement across all codes, with > 80% agreement considered acceptable for such methodologies (Miles & Huberman, 1994). Nonetheless, a subsequent discussion was held between coders to ensure no systemic differences contributed to disagreements.

Total verbalized content (i.e., transcribed word count), and data categorised into primary and secondary themes were analysed across TT quartile and group. Only select secondary themes were subject to analysis. A theoretical rationale for assessing these secondary themes is provided in the supplementary materials (Item 3). To assess how thoughts captured related to affect, an analysis was performed as above with the added categorisation of verbalizations occurring in either a positive or negative affective state. Verbalization count was converted into a percentage for each primary theme to control for differences in time spent in a positive and negative affective state. The data was subject to the same testing and criteria described above. Non-parametric testing was performed on data where assumptions of normality were violated. Pearson’s r is reported as a measure of effect size for *post hoc* pairwise comparisons. For conciseness, only significant findings are reported for the analysis of verbalisations by primary and secondary themes. Due to a technical issue with the recording equipment, one Non-ET participant’s recording was illegible, therefore their data was removed from this section of the analysis.

Table 2.2 Median (IQR) Verbalizations of Secondary Themes by Trained Status, With Definitions.

Primary theme	**Secondary theme**	**Non-ET**	**ET**	**Overall**	**Definition**
Internal sensory monitoring	Breathing	6.50 (2.00)	6.50 (2.00)	6.50 (1.00)	References to breathing or respiration (e.g., “breathing is quite laboured”).
	Comfort[a]	1.00 (0.25)	2.00 (2.50)	1.00 (1.25)	References to feelings of mental or physical comfort (e.g., “this handlebar position is much more comfortable”).
	Discomfort & pain	14.00 (4.75)	14.00 (3.00)	14.00 (3.00)	References to feelings of mental or physical discomfort (e.g., “legs are very sore!”).
	Hydration	3.50 (1.50)	5.50 (1.75)	4.50 (2.25)	References to taking in, or requiring fluids (e.g., “just have a quick drink of water”).
	Fatigue	5.50 (1.25)	3.50 (2.00)	5.00 (2.25)	References to physical or mental fatigue (e.g., “fatigue building in the quads”).
	Temperature	6.50 (3.75)	10.00 (4.25)	8.50 (4.50)	References to environmental or body temperature (e.g., “getting pretty sweating”).
	Heart rate	5.00 (3.25)	11.50 (3.75)	8.50 (5.25)	References to heart rate (e.g., “heart rate is at 180”).
	Rating of perceived exertion[a]	3.00 (0.75)	5.50 (2.00)	4.00 (2.50)	References to perceived exertion or effort (e.g., “I’m pushing really hard”).
	Affect[a]	4.00 (0.50)	13.00 (2.25)	5.00 (9.00)	References to positive/negative feelings (e.g., “I’m feeling really good”).
Active self-regulation	Speed	10.00 (6.00)	9.00 (2.50)	9.00 (5.50)	References to speed feedback (e.g., “keep the speed at 38 kph”).
	Power output	6.00 (1.00)	31.50 (2.75)	16.50 (25.25)	References to power output feedback (e.g., “aim for 260

					watts”).
	Pace	10.50 (3.00)	17.00 (6.00)	13.00 (5.25)	References to pacing behaviour (e.g., “nice and steady, maintain this pace”).
	Increase pace	7.50 (2.00)	5.50 (4.25)	7.00 (3.00)	Specific references to increasing pace (e.g., “all-out effort in the last 1 km”).
	Decrease pace	1.00 (1.00)	0.00 (0.75)	1.00 (1.50)	Specific references to decreasing pace (e.g., “ease the pace for a negative split”).
	Self-regulation strategy[a]	20.00 (4.00)	45.00 (15.25)	21.50 (27.00)	References to self-regulatory efforts or strategies (e.g., “just relax and stay in control”).
	Motivation	62.00 (8.75)	47.50 (32.00)	59.00 (23.50)	Refences to self-motivational efforts or strategies (e.g., “12 km’s done, great effort!”).
	Cadence	6.50 (3.75)	8.50 (6.75)	7.50 (4.25)	References to cadence feedback (e.g., “keep RPM below 90”).
	Gearing	6.50 (2.50)	5.50 (2.25)	6.00 (2.75)	References to gearing feedback (e.g., “I can up the gear closer to the end”).
	Technique	6.00 (2.25)	24.50 (3.25)	14.50 (17.75)	References to technical aspects of cycling (e.g., “maintain a smooth pedalling action”).
Outward monitoring	Time	18.00 (5.00)	5.00 (3.75)	14.50 (12.00)	References to time, including expected finishing time (e.g., “this could be a personal best time”).
	Distance	46.00 (6.50)	51.50 (29.50)	46.00 (16.25)	References to distance feedback (e.g., “at 5 km’s now, well into the second quartile”).
Distraction	Involuntary distraction[a]	19.50 (7.75)	12.00 (3.00)	14.50 (6.25)	Refences to non-deliberate focus on stimuli (e.g., “the lights are bright in this room”).

Intentional distraction[a]	5.00 (3.25)	3.00 (0.25)	3.50 (1.50)	References to deliberate focus on stimuli (e.g., “I’ll fixate on that clock for a moment”).
Scenery & course information[a]	4.50 (5.00)	4.00 (4.50)	4.50 (4.25)	References to information on screen. Does not include performance feedback (e.g., “there’s a bend coming up”).
Think aloud[a]	2.50 (1.25)	2.00 (2.50)	2.50 (1.50)	References to use of think aloud (e.g., “thinking aloud and cycling is difficult!”).

Note. ET = endurance trained, Non-ET = non-endurance trained.
[a]Secondary themes included through abductive analysis.

Transparency and Openness

This study was not preregistered. Methodology, materials and data analysis are described sufficiently to allow for replication, and the authors followed the Journal Article Reporting Standards (JARS) for Mixed Methods Article Reporting Standards (APA, 2022).

Results

TA Feasibility

Time-trial performance. No significant interaction was observed for trial*trained status for finish time, $F(1, 13) = 1.09$, $p = .32$, $\eta p^2 = .077$ and w/kg, $F(1, 13) = 0.33$, $p = .58$, $\eta p^2 = .025$, nor for trial*quartile for w/kg, $F(1.66, 21.61) = 0.11$, $p = .87$, $\eta p^2 = .008$. A significant main effect was observed for trained status for both finish time, $F(1, 14) = 14.73$, $p = .002$, $\eta p^2 = .51$ and w/kg, $F(1, 14) = 14.72$, $p = .002$, $\eta p^2 = .51$. A significant main effect was observed for quartile for w/kg, $F(1.59, 22.23) = 4.68$, $p = .027$, $\eta p^2 = .25$. No significant main effect was observed for trial for both finish time, $F(1, 13) = 0.14$, $p = .72$, $\eta p^2 = .011$ and w/kg, $F(1, 13) = 1.29$, $p = .28$, $\eta p^2 = .090$. See Table 2.3 for mean finish time and w/kg across trial and trained status.

Table 2.3 Mean (*SD*) Time-Trial Finish Time and Watts per Kilogram by Trial and Trained Status.

Performance measure	**No think aloud trial**	**Think aloud trial**

	ET	Non-ET	Overall	ET	Non-ET	Overall
Finish time (secs)	1578.83 (73.44)	1793.85 (139.53)	1686.34 (154.70)	1585.35 (69.54)	1780.35 (131.86)	1682.85 (143.21)
Watts per kilogram	3.42 (0.61)	2.47 (0.35)	2.94 (0.69)	3.38 (0.59)	2.46 (0.36)	2.92 (0.67)

Note. ET = endurance trained, Non-ET = non-endurance trained.

No significant interaction was observed for trial*trained status for both cadence, $F(1, 13) = 1.02$, $p = .33$, $\eta p^2 = .073$ and SpinScan, $F(1, 13) = 0.15$, $p = .71$, $\eta p^2 = .011$. A significant main effect was observed for trained status for cadence, $F(1, 14) = 5.26$, $p = .038$, $\eta p^2 = .27$, but not for SpinScan, $F(1, 14) = 2.64$, $p = .13$, $\eta p^2 = .16$. No significant main effect was observed for trial for both Cadence, $F(1, 13) = 0.70$, $p = .42$, $\eta p^2 = .051$ and SpinScan, $F(1, 13) = 0.38$, $p = .55$, $\eta p^2 = .028$. Significant *post-hoc* comparisons for TT performance results are presented in Table 2.4.

Flanker task performance. For accuracy, a significant interaction was observed for trial*session, $F(1, 13) = 4.94$, $p = .045$, $\eta p^2 = .28$, but not for trial*trained status, $F(1, 13) = 0.83$, $p = .38$, $\eta p^2 = .060$. However, follow-up testing found the mean difference in response conflict between trials pre-exercise ($M = -0.004$, $SD = 0.049$) was not significantly different to scores post-exercise ($M = 0.015$, $SD = 0.046$), $t(15) = -1.32$, $p = .21$, $d_z = 0.33$. No significant main effect was observed for session, $F(1, 14) = 0.013$, $p = .91$, $\eta p^2 = .001$, trial, $F(1, 13) = 0.47$, $p = .51$, $\eta p^2 = .035$, and trained status, $F(1, 14) = 1.22$, $p = .29$, $\eta p^2 = .080$.

For RT, no significant interaction was observed for trial*session, $F(1, 13) = 0.056$ $p = .82$, $\eta p^2 = .004$ and trial*trained status, $F(1, 13) = 0.021$, $p = .89$, $\eta p^2 = .002$. No significant main effect was observed for session, $F(1, 14) = 0.56$, $p = .47$, $\eta p^2 = .039$, trial, $F(1, 13) = 0.37$, $p = .56$, $\eta p^2 = .027$, and trained status, $F(1, 14) = 0.005$, $p = .95$, $\eta p^2 = .001$. See Item 4 of the supplementary materials for full flanker task data.

Psychophysical measures. No significant interaction was observed for trial*trained status for RPE, $F(1, 13) = 1.02$, $p = .33$, $\eta p^2 = .073$ and affect, $F(1, 13) = 0.078$, $p = .79$, $\eta p^2 = .006$, nor for trial*quartile for RPE, $F(1.72, 22.41) = 0.14$, $p = .84$, $\eta p^2 = .011$ and affect, $F(1.58, 20.58) = 0.28$, $p = .71$, $\eta p^2 = .021$. A significant main effect was observed for quartile for both RPE, $F(1.70, 23.73) = 86.55$, $p < .001$,

ηp^2 = .86 and affect, *F*(1.44, 20.10) = 25.39, *p* < .001, ηp^2 = .65. No significant main effect was observed for trial for both RPE, *F*(1, 13) = 0.59, *p* = .46, ηp^2 = .044 and affect, *F*(1, 13) = 1.32, *p* = .27, ηp^2 = .092, nor for trained status for both RPE, *F*(1, 14) = 1.54, *p* = .24, ηp^2 = .099 and affect, *F*(1, 14) = 0.005, *p* = .94, ηp^2 = .001.

For ROF, no significant interaction was observed for trial*trained status, *F*(1, 13) = 0.001, *p* = .99, ηp^2 = .001 and trial*session, *F*(1, 13) = 0.003, *p* = .96, ηp^2 = .001. A significant main effect was observed for ROF for session, *F*(1, 14) = 150.91, *p* < .001, ηp^2 = .92 and trained status, *F*(1, 14) = 4.68, *p* = .048, ηp^2 = .25, but not for trial, *F*(1, 13) = 0.14, *p* = .72, ηp^2 = .011. Significant *post-hoc* comparisons for psychophysical measures are presented in Table 2.4.

Table 2.4 Significant *Post-hoc* Comparisons for Performance and Psychophysical Measures.

Measure	**Main effect**	***Post-hoc* comparisons (*M, SD*)**	**Effect size (d_s/d_z)**
Performance	Finish time (secs)		
	Trained status**	ET (1582.09, 68.71) < Non-ET (1787.1, 134.59)**	1.92
	PO (w/kg)		
	Trained status**	ET (3.4, 0.59) > Non-ET (2.46, 0.35)**	1.94
	Trial split**	Q3 (2.9, 0.67) < Q4 (3.05, 0.69)*	1.09
	Cadence (r.min^{-1})		
	Trained status*	ET (95.99, 9.55) > Non-ET (81.96, 14.42)*	1.15
Psychophysiology	RPE (a.u.)[a]		
	Trial split***	Q1 (14.09, 2.47) < Q2 (15.59, 1.98)***	1.48
		Q2 (15.59, 1.98) < Q3 (17.00, 1.73)***	2.05
		Q3 (17.00, 1.73) < Q4 (19.03, 1.82)***	1.68
	Affect (a.u.)[a]		
	Trial split***	Q1 (1.38, 1.45) > Q2 (0.09, 1.71)***	1.39
		Q2 (0.09, 1.71) > Q3 (-0.97, 1.87)**	1.30
	ROF (a.u.)		
	Session***	Pre-TT (1.72, 1.09) < Post-TT (7.72, 1.14)***	4.61
	Trained status*	ET (5.03, 0.65) > Non-ET (4.41, 0.50)*	1.08

Note. ET = endurance trained, Non-ET = non-endurance trained, PO = power output, Q = quartile, r.min^{-1} = revolutions per minute, ROF = Rating Of Fatigue, RPE = Rating of

Perceived Exertion, TT = time-trial, w/kg = watts per kilogram.
[a]Only comparisons to the previous quartile are reported.
**p* < .05, ***p* < .01, ****p* < .001.

TA Content

Verbalized content. For total verbalized content, no main effect was found for quartile, *F*(1.79, 23.28) = 1.28, *p* = .29, ηp^2 = .090 and trained status, *F*(1, 13) = 0.058, *p* = .81, ηp^2 = .004.

Primary theme verbalizations. For primary themes overall, a significant main effect was observed for theme, χ^2(3) = 29.16, *p* < .001. Significantly more active self-regulation verbalizations (M_{rank} = 3.53) were made by participants compared to internal sensory monitoring (M_{rank} = 1.93, *p* < .001, *r* = .84) and distraction (M_{rank} = 1.33, *p* < .001, *r* = .85) verbalizations. Likewise, significantly more outward monitoring verbalizations (M_{rank} = 3.20) were made by participants compared to internal sensory monitoring (*p* = .001, *r* = .79) and distraction (*p* < .001, *r* = .88) verbalizations. A significant main effect was observed for verbalizations by quartile for active self-regulation, χ^2(3) = 8.83, *p* = .029 and OM, χ^2(3) = 14.20, *p* = .002. Significantly more outward monitoring verbalizations were made by participants in quartile 4 (M_{rank} = 3.50) versus quartile 1 (M_{rank} = 1.87, *p* = .006, *r* = .69). Concerning group differences by quartile, significantly more outward monitoring verbalizations were made by Non-ET (M_{rank} = 11.21) versus ET (M_{rank} = 5.19) participants in quartile 1 (*U* = 5.50, *p* = .007, *r* = .68). All remaining results were non-significant when accounting for the Bonferroni correction.

Secondary theme verbalizations. A significant main effect was observed for verbalizations by quartile for motivation, χ^2(3) = 25.27, *p* < .001, distance, χ^2(3) = 17.61, *p* < .001, and involuntary distraction, χ^2(3) = 8.72, *p* = .028. Significant *post-hoc* comparisons of quartiles for secondary themes are presented in Table 2.5. Significantly more PO verbalizations were made by ET (M_{rank} = 10.31) versus Non-ET (M_{rank} = 5.36) participants overall (*U* = 9.50, *p* = .031, *r* = .56). All remaining results were non-significant when accounting for the Bonferroni correction.

Table 2.5 Significant *Post-hoc* Quartile Comparisons for Secondary Themes.

Secondary theme	**Quartile comparison (M_{rank})**	**Wilcoxon rank (*Z*)**	**Significance (*p*)**	**Effect size (*r*)**

Distance	Q4 (3.57) > Q3 (2.47)	-2.67	.005	.69
	Q4 (3.57) > Q2 (2.33)	-2.73	.004	.71
	Q4 (3.57) > Q1 (1.63)	-3.05	.001	.79
Motivation	Q4 (3.67) > Q3 (2.60)	-3.07	.001	.79
	Q4 (3.67) > Q2 (2.20)	-3.05	.001	.79
	Q4 (3.67) > Q1 (1.53)	-3.07	.001	.79
	Q3 (2.60) > Q1 (1.53)	-2.68	.006	.69
Involuntary distraction	Q4 (1.90) < Q1 (2.83)	-2.54	.008	.65

Note. Q = quartile

Primary theme verbalizations and affective state. Significantly more distraction verbalizations were made in a positive (M_{rank} = 8.18) versus negative (M_{rank} = 5.00) affective state ($Z = 2.35$, $p = .017$, $r = .61$). All remaining results were non-significant when accounting for the Bonferroni correction.

Discussion

TA Feasibility

Given the emergent nature of TA methods in endurance performance research, a key aim of this study was to investigate the impact of TA on endurance performance and vice versa. Contrary to the researchers' predictions, the difference in performance between the two experimental trials was not significant, with a w/kg difference of 0.02 and a time difference of 3.5 seconds between conditions. Pacing followed a similar pattern across the TT's, with a significant increase in w/kg from 12-16 km. This is an indication of a reservation of energy expenditure in quartile 3 to ensure sufficient reserves for an end-spurt (Tucker et al., 2006). Therefore, it would appear that level 2 TA verbalization did not impact on full-effort TT performance or pacing, referred to as reactivity. In addition, with TA prevalence accounted for, the results suggest that the lack of reactivity observed is not related to the frequency of verbalisation by participants. The findings are contrary to those observed in Fox et al.'s (2011) review, which highlighted a possible slowing of task completion time (when time is a measure of performance) when using TA. In contrast, the research supports recent findings showing no detriment to cycling performance at various exercise intensities under TA conditions (Whitehead et al., 2022).

The above findings are particularly promising when viewed through the lens of theories concerning attentional focus and cognition in exercise performance.

Affect scores were similar across experimental trials. On average, participants spent the second half of the TT's in a negative affective state. Therefore, any possible cortical changes resulting in compromised self-regulation of effort and metacognitive processes (Brick, MacIntyre, & Campbell, 2016), as proposed by the RAH model (Dietrich & Audiffren, 2011), appear unaffected by the addition of TA. This finding is reinforced by the similar pacing strategy adopted by participants across the trials. Moreover, cadence and SpinScan scores (i.e., pedalling efficiency) were not found to be significantly different across the trials. This suggests that using TA did not negatively impact on biomechanics (i.e., the automatic process of efficient pedalling) as a consequence of an internal focus (Schücker et al., 2016).

No difference in performance or efficiency was found across the TT's for both ET and Non-ET participants. Through years of practice, it is reasonable to suggest that cycling is an automated skill for ET cyclists. Such automaticity 'frees up' attentional resources which an athlete can devote to a secondary task, such as thinking aloud (Beilock et al., 2002). Alternatively, any additional activity that may interfere with automated skill execution could be detrimental to performance through the interruption of a 'flow state' (Jackson, 1995) or external focus of attention (Wulf & Lewthwaite, 2016). Therefore, it does not appear that performance was subject to such interference by using TA, nor hindered by a finite capacity of 'free' attentional resources to dedicate to thinking aloud.

Alongside similar performance and contrary to the researchers' predictions, no significant differences between the two experimental trials were observed for RPE, affect, or ROF scores. This suggests no change in perceptual experience and uncompromised TT performance when using TA. The only notable difference observed was an overall higher ROF score for ET participants, albeit a non-significant finding which may be related to the greater training load reported by ET participants (Budgett, 1998). Conversely, Whitehead et al. (2022) observed some benefits to economy (lower heart rate and blood lactate) and perceived exertion (lower RPE) through using TA. These mixed findings suggest that future work into TA as an aid to self-regulating endurance performance is warranted.

Concerning flanker task performance, no difference in response conflict, and therefore response inhibition capacities was observed between the experimental trials. An interaction was observed between trial and session, however the follow up analysis was not significant. Therefore, no evidence was observed to suggest that TA is cognitively taxing to executive control resources when measured following self-paced endurance performance. However, future research would be valuable to investigate whether a cognitive 'debt' may bear out over longer exercise durations, in which any hypofrontality is proposed to be greater (Dietrich & Audiffren, 2011).

TA Content

The second aim of this research was to gain a deeper understanding of endurance performance and pacing through the assessment of TA data in tandem with measures of psychophysiology and cognition. Firstly, contrary to the researcher's predictions, no significant differences were found concerning overall verbalized content across ET status or TT quartiles. However, there was an observable downward trend in verbalizations in the second half of the TT. This aligns with Whitehead et al.'s (2017) research, where significantly more verbalizations were found in the first versus last quartile. Moreover, similar to Massey et al. (2020), trained participants verbalized less than their untrained counterparts in the first half of the TT. However, there is no clear indication that a change in cognition or attention influenced TA prevalence as a function of cycling experience or fitness level.

The prevalence of active self-regulation and outward monitoring verbalizations were significantly greater than internal sensory monitoring and distraction verbalizations. This is unsurprising, as together they encompass the two most predominant secondary themes, distance (outward monitoring) and motivation (active self-regulation), which combined accounted for over 34% of the total verbalizations coded. Supporting the researchers' predictions and in alignment with Whitehead et al. (2018), active self-regulation was the most prevalent primary theme, despite participants completing an outdoor TT in Whitehead et al.'s (2018) experiment. In addition, Massey et al. (2020) found active self-regulation was the most prevalent theme among trained persons in their lab-based experiment, however outward monitoring was the most prevalent theme among their untrained population. Moreover, when in competition with a virtual competitor, there was a significant increase in active self-regulation verbalizations for trained versus untrained participants. These similarities and differences may simply reflect the difficulty in establishing definitive conclusions from the relatively small amount of research within this field to date. Alternatively, they could reflect differences in environmental conditions (i.e., competitor presence) and participant characteristics (i.e., differences in experience or expertise).

In respect to task unrelated verbalizations, partially supporting the researchers' predictions, involuntary distraction decreased across the TT, with a significant decrease observed in quartile 4 versus quartile 1. Therefore, the attentional focus of participants was fixated less on task-unrelated thoughts in the final compared to the opening stages of the TT. Although a steady effort was adopted by participants across the TT, the associated increased salience of fatigue-related sensations (e.g., increasing soreness in the working muscles) may have drawn participant's focus more inward (Hutchinson & Tenenbaum, 2007). These data trends are also analogous to the RAH model (Dietrich & Audiffren, 2011), as higher-order cognitive control of a distracting external focus may not be possible when hypofrontality occurs around the ventilatory threshold. If we assume that this shift in attentional resources holds true, one might have expected a continuous upturn or plateau in internal sensory monitoring verbalizations in the final quartile. This may relate to the observed changes in verbalizations that reference different aspects of cognition taking precedence in the final stages of the TT.

Concerning active self-regulation, verbalizations remained steady between quartiles 1 and 2, before increasing in the second half of TT. A notable increase from quartile 2 to 4 was largely attributable to a change in motivation-related verbalizations. Supporting the researchers' predictions, motivational verbalizations increased quartile-on-quartile and were significantly greater in quartile 4 relative to the previous quartiles, mirroring the findings of Whitehead et al. (2018). The above trends are more interesting when analysed in tandem with outward monitoring verbalizations. A greater number of outward monitoring verbalizations were observed in quartile 4 relative to quartile 1. As predicted, this is explainable by a significant spike in distance-related verbalizations in the final quartile, indicating a particular focus on this feedback information in the closing stages of the TT. Notably, Whitehead et al. (2017) also found a significant increase in distance verbalizations as the TT progressed.

The increase in active self-regulation verbalizations across the TT may be indicative of participants adopting psychological strategies to increase effort or better regulate pacing. Interestingly, it would appear that self-regulatory efforts are most helpful to performance in the more difficult later stages of endurance events (e.g., Barwood et al., 2015; Brick et al., 2019). In addition, the coincidence of distance and motivation verbalizations increasing in the final quartile may indicate a relationship. Evidence for this is provided by the co-occurrence of distance and motivation verbalizations in sequence during the final quartile. For example, “Last 500m, let’s go for it” (participant 16) and “1 more kilometre, don’t fade!” (participant 12) both demonstrate participants referring to the distance remaining prior to using motivational self-talk. Future work could focus on the relationship between performance feedback integration, psychological strategies, and pacing.

Concerning the division of verbalizations by affect, in partial support of the researchers’ predictions, the only significant finding related to a greater off-task attentional focus in a positive versus negative affective state. Once more, the findings can be understood by shifts in attention processes highlighted previously (Hutchinson & Tenenbaum, 2007). However, for full support of this proposition, one might also have expected to observe a greater number of internal sensory monitoring verbalizations in a negative affective state. The need to self-regulate effort and focus on key performance feedback to optimise pace may ‘override’ such physiological sensations during the final quartile. Interestingly, this would suggest that some outward monitoring, mostly to distance feedback, is achievable in these difficult later stages. This is perhaps governed by the greater importance of this information to endurance performers with end-point knowledge (e.g., Wingfield et al., 2018).

There were significantly greater PO-related verbalizations among the ET group, supporting the researchers’ predictions and echoing recent findings (Massey et al., 2020). This is unsurprising given the importance of PO feedback to cycling performance (Hettinga et al., 2012) and that blinding to performance feedback (including PO) hinders cycling performance (Wingfield et al., 2018). When such feedback was presented to participants, PO was strongly associated with neural activity in the PFC, which is implicated in the top-down regulation of endurance performance (Hyland-Monks et al., 2018). Therefore, it appears that through experience, trained cyclists become better attuned at paying attention to PO to self-regulate effort. Additionally, as predicted, more outward monitoring verbalizations were made by ET versus Non-ET participants in the first quartile, indicating a greater focus on task demands by trained persons during the earlier stages of the TT. It should be noted that further differences between ET and Non-ET participants were predicted in line with previous findings (Massey et al., 2020; Whitehead et al., 2018). The reason for these differences is unclear but could relate to the nascency of this work or differences in participant characteristics and task demands, as previously suggested. However, both the present study and the aforementioned research (Massey et al., 2020; Whitehead et al., 2018) used similar protocols and recruitment criteria, and all found similarly large differences in TT performance between groups, with large effect sizes observed.

Limitations and Future Directions

Moving forward, future research could build on this work by addressing its limitations. Although efforts were made to engage participants via a virtual course, attempts to capture naturally occurring thought processes in a laboratory environment should come with a caveat of some compromise to ecological validity. Therefore, assessment of TA feasibility in more realistic outdoor conditions (e.g., Whitehead et al., 2018) and with competitive features (e.g., Massey et al., 2020) would be useful additions. Future work could also look to exploit the increasing interest in virtual reality technology and indoor simulation training for endurance sports by incorporating multimodal elements of the environment (e.g., visual and sound stimuli) and more intimate user perspectives (e.g., point-of-view perspectives) to increase the immersiveness of exercise (Neumann et al., 2018).

Following on, although minimising disruption from the experimenter was important in this study, other similar work has used intervention by verbal instruction to encourage the continuous use of TA (e.g., Whitehead et al., 2022). Although a covariate analysis was used to account for the effect of TA prevalence on possible reactivity, verbal instruction may be a further means to ensure verbalisation is maintained despite the competing demands of exercise performance. Moreover, with TA being an ‘unnatural’ and potentially self-conscious practice, it is possible that efforts to familiarise participants as recommended (Eccles & Arsal, 2017) may not be sufficient to overcome these issues. Therefore, longer practice and familiarisation time may remove these barriers and result in richer insights.

Furthermore, it is also worth noting the possible limitations of TA in truly capturing thought processes. Micklewright, Kegerreis et al. (2017) propose a dual-process approach to determining pacing behaviour, with decisions made through both automatic processes and cognitively taxing executive control. Therefore, information at the unconscious and subconscious level that influences pacing behaviour could be left unaccounted for by TA. Other methodologies used in conjunction with TA, such as the measurement of cortical activity (Perrey & Besson, 2018) and the recently adopted eye-tracking technology (Massey et al., 2020) could help address aspects of non-explicit cognition.

Conclusion

Concerning TA feasibility, no detriment to performance or perceptual experience was found when participants were required to use TA for a 16 km cycling TT. Thus, one can reasonably conclude that TA is a feasible methodology to adopt without compromise to endurance performance (i.e., reactivity). Promisingly, no significant compromise to cognitive performance was evident when TA was used. However, the facilitatory effect of exercise on RT performance was smaller in the TA trial, which could reflect a possible prefrontal-dependent cognitive ‘debt’ acquired through using TA. Thought processes became less outwardly orientated as the TT progressed, possibly reflecting affective changes and cerebral perturbations. Moreover, verbalizations indicate that self-regulatory efforts and end-point knowledge become more salient in the closing stages. In addition, attending to performance feedback to gauge effort is most likely developed through experience. Future research should look to improve the immersiveness of TA investigations and use TA in conjunction with other methods to measure different aspects of cognitive processes underpinning pacing.

Chapter 3 The Role of Executive Function in the Self-Regulation of Endurance Performance: A Critical Review

Parts of this chapter have been published in a peer-reviewed journal.

Hyland-Monks, R., Cronin, L., McNaughton, L., & Marchant, D. (2018). The Role of Executive Function in the Self-Regulation of Endurance Performance: A Critical Review. *Progress in Brain Research, 240,* 353–370. https://doi.org/10.1016/bs.pbr.2018.09.011

Abstract

Research has outlined how self-regulation is crucial to the decision-making processes and pacing of endurance performance. There is evidence to suggest that executive function is implicated in self-regulatory processes, as the two are conceptually similar and share common brain regions such as the prefrontal cortex. This review draws upon various research domains to argue that executive function underlies the top-down self-regulation of endurance tasks. Indeed, executive functioning capacity may explain differences in endurance performances. Although contentious, there is evidence to suggest a hypofrontality effect during endurance exercise. Furthermore, research has highlighted that psychological interventions, the training of executive functions, and transcranial direct stimulation can induce prefrontal cortex changes and 'boost' executive functioning, ultimately enhancing the self-regulation of endurance performance. Future directions for research are proposed with the aim of stimulating investigations that will further elucidate the importance of executive functioning and self-regulation to endurance performance.

Introduction

The effective self-regulation of endurance exercise places unique challenges on the brain and its cognitive capacities, through on-going decision-making and anticipatory processes aimed at distributing work rate (Renfree et al., 2014). As outlined and explored as part of Chapter 2, TA can be used to explore athlete cognition as it pertains to the pacing of endurance performance. For instance, the findings indicated that cyclists paid particular attention to the distance remaining in the closing stages of a race, which possibly reflects the salience of this information to regulate output at this time. However, as discussed in Chapter 2, there are several limitations to using TA. These drawbacks include the ability of TA to capture subconscious processes of decision-making during performance. Therefore, we may need to look elsewhere for methods to explore the cognitive apparatus that governs the decision-making of energy regulation. Following on, effective self-regulation during endurance activity is thought to require both proactive, goal-driven processes and reactive, stimulus-driven processes (Brick, MacIntyre, & Campbell, 2016), however little is known of the underpinning cognitive mechanisms. Indeed, Furley and Wood (2016) highlight that executive functions such as working memory have not been embraced within sports performance research. As a central executive function, working memory and decision-making are important to human goal-directed behaviour, alongside capacities such as planning, inhibition, problem-solving, and selective and sustained attention. Therefore, this review aims to explore the self-regulation of endurance performance through the perspective of executive functioning to inform our understanding of important mechanisms. The limited consideration of executive function in the context of pace regulation is interesting and timely given that: (i) The prefrontal cortex (PFC) may play a role in exercise regulation through integrating afferent feedback from cardiovascular organs and locomotor muscles to guide decision-making (Robertson & Marino, 2016), and (ii) The PFC is a key brain structure implicated in the top-down signalling of executive functions (Funahashi & Andreau, 2013).

Executive Function and Self-Regulation

Executive function refers to ‘higher-level’ cognitive processes that exert top-down regulation of ‘lower-level’ cognitive processes to support flexible and adaptive goal-directed behaviour (Alvarez & Emory, 2006). Miyake et al.'s (2000) latent variable analysis revealed three distinct, yet related executive functions: ‘updating’, ‘inhibition’ and ‘shifting’. Updating is synonymous with working memory and relates to the ability to maintain information within memory for quick retrieval, along with the ability to shield this information from distraction. Inhibition refers to the ability to deliberately inhibit or override dominant, automatic, or pre-potent responses. Shifting is the ability to switch between multiple tasks, operations, or mental sets. Hofmann et al., (2012) argue that self-regulatory processes are sub-served by executive functions to enable effective goal-directed behaviour, with a minimum temporal perspective, encompassing achievement-related behaviours, personal strivings, and the regulation of shared goals. Self-regulation is purported to entail three main components (Baumeister & Heatherton, 1996): (i) Ideas, goals, and other conceptions of possible states; (ii) A feedback loop to assess the discrepancies between actual versus ideal standards; (iii) The capacity to achieve self-regulation despite obstacles and temptations. It is the third component of self-regulation that Hofmann et al. (2012) believe executive functions may contribute most to; however, these researchers highlight evidence linking the three executive functions and self-regulation.

To begin with, working memory may subserve the representation of goals and ideals, and the means by which goals and ideals can be met (Miller & Cohen, 2001). Working memory is thought to play a key role in executive attention (Miller & Cohen, 2001). In what is termed ‘passive’ inhibition, executive attention is thought to contribute to the ‘shielding’ of goals from distractions through sustained attention upon goal-relevant stimuli of greater salience (Dreisbach & Haider, 2009). In addition, working memory has been implicated in emotional regulation and cognitive appraisal (Gross, 1998), which may be of significance to the psychophysiological determination of endurance performance. Intriguingly, a cognitive reappraisal strategy to regulate emotion during exercise improved emotional arousal and lowered perceived exertion during steady-state running versus distraction and emotion regulation strategies (Giles et al., 2018), although these improvements were not reflected in prefrontal haemodynamic changes. Moreover, those with lower impulse control performed worse on implicit reaction time measures of marker variables for individual’s impulsive predispositions (Hofmann et al., 2009). In addition, poorer response inhibition was associated with lower pain tolerance as measured by cold pressor task performance (Karsdorp et al., 2014). Therefore, response inhibition has clear implications for impulsive control, and thus maintaining goal-directed behaviour despite competing impulses, desires, and temptations. In respect to shifting, Goschke (2003) developed the notion of a self-regulatory dilemma. Goschke (2003) suggested that there is a delicate balance required between ‘rigid’ goal pursuit which working memory and inhibitory processes facilitate, and flexibility in goal-obtainment means (‘means-shifting’) or pursuit of other goals (‘goal-shifting’). Means-shifting represents the abandonment of a sub-optimal method of goal-pursuit to pursue an alternative and superior method. Goal-shifting represents disengagement from pursuing one goal to focus on another goal. Therefore, in the context of self-regulating an endurance race (e.g., a marathon), a performer may have to block out numerous distractions (e.g., crowd noise) to ensure the pre-race strategy is retained in the working memory (updating), whilst resisting the temptation to slow down when highly fatigued (inhibition) and adjusting a pacing strategy to over-take an opponent (shifting).

Given the inherent relationship between executive function and self-regulation, the purpose of this review is to draw upon various research strands to uniquely show how the former may underlie the latter to contribute to the effective pacing of endurance performance. Firstly, the importance of self-regulation to pacing will be highlighted before a detailing of research suggesting a relationship between executive functions and endurance performance. The neurological underpinnings for the effect of exercise on executive functions will also be covered, alongside potential avenues to improve or maintain executive functioning to aid endurance performance.

Self-Regulation and Endurance Performance

One key component of endurance performance is pacing. In its simplest form, pacing refers to the method by which an athlete distributes work and energy throughout an exercise task (Abbiss & Laursen, 2008). Effective pacing is crucial to endurance performance; for instance, a high motivational drive could be indulged without due regard for homeostatic control, resulting in suboptimal performance through premature neuromuscular failure. In the most severe but rare instances, this failure can be catastrophic and is described by St. Clair Gibson et al. (2013) as the ‘foster collapse’. In contrast, very conservative pacing will result in a greater chance of race completion, but may result in underperformance as a faster pace could have been adopted. Thus, given the importance of pacing, explorations attempting to better understand the regulation of endurance activity have long been theorized. Joyner and Coyle (2008) have provided an overview of the physiological characteristics that contribute to endurance performance. Specifically, they conclude that maximum oxygen consumption, lactate threshold and economy (or efficiency) are the key factors predicting endurance performance, and as such, the running velocity or cycling power output that can be achieved over a given period of time. However, the authors acknowledge the probability that there is a complex interplay between motivational and sociological factors that further contribute to explaining differences in athletic performance. However, in the absence of accounting for these factors, no model can explain decision-making processes involved in pacing.

Other models of endurance performance, covered more extensively in Chapter 1, do converge on a conscious or sub-conscious self-regulation of pacing. According to the central governor model (Noakes, 2004, 2012a, 2012b), afferent feedback from numerous physiological systems is collated to determine a ‘conscious’ rating of perceived exertion (RPE). This RPE is continuously compared to a subconscious ‘template’ related to the expected exertion to be experienced at given points during exercise of a known distance. However, this supposed subconscious central governor cannot accommodate for motivational and cognitive factors involved in the conscious decision-making and adjustment of pacing during performance. More analogous with self-regulatory processes underpinning pacing is the psychobiological model of endurance performance (Marcora, 2010). The psychobiological model is an effort-based decision-making model which theorizes that the conscious regulation of pace is determined primarily by effort perception and potential motivation.

Brick, MacIntyre, and Campbell (2016) provide a cognitive perspective on the importance of self-regulation to endurance performance. The framework features two modes of cognitive control. Proactive control involves the goal-directed processing of information so that attention, perception and action are biased favourably towards goal obtainment. Reactive control is automatic and transient, and only engaged when required. Relative to proactive control, reactive control is less demanding of cognitive resources (e.g., executive functions). As detailed in Chapter 1, Brick, Campbell et al. (2016) demonstrated that during a 3 km run, when the pace was externally controlled, participants predominately utilised reactive control and their heart rate was lower, reflecting a difference in cognitive strategies adopted, and thus engagement of executive function. Although not a direct assessment of Brick, MacIntyre and Campbell’s (2016) work, recent research by Chacko et al. (2020) has indicated that moderate-to-vigorous aerobic exercise (i.e., 30 minutes of cycling at 65-70% heart rate reserve) modulates neural mechanisms of reactive, but not proactive control as measured by electroencephalogram (EEG). Therefore, in support of Brick, Campbell et al. (2016), brain areas responsible for perceptual awareness (e.g., insular cortex) and selective attention (e.g., parieto-occipital areas) were more engaged during prescribed, as opposed to self-paced exercise..

Informed by this, Brick et al. (2014) proposed a metacognitive framework of attentional focus and cognitive control for exercise self-regulation. According to the framework, outlined in Chapter 1, metacognitive skills (i.e., planning and monitoring) and experiences (e.g., feelings and judgments) are key to the self-regulation of endurance performance. This framework encapsulates research highlighting that self-regulatory cognitions are associated with more effective pacing of endurance performance (Clingman & Hilliard, 1990; Rushall et al., 1988) and enhanced movement economy during endurance tasks (Crews, 1992; Martin et al., 1995). Integrating contemporary perspectives on metacognitions, Roebers (2017) points to three interacting metacognitive processes: metacognitive knowledge (e.g., knowledge of cognitive processes; ‘thinking about thinking’), procedural metacognition (e.g., subjective assessment; monitoring of ongoing cognitive processes) and metacognitive control (e.g., the regulation of cognitive activities). Interestingly, as evident in the definitions provided, there are conceptual similarities between executive function and metacognition. For instance, they are both considered higher-order, controlled cognitive processes, underpinned by sub-processes working in tandem to ensure goal-directed behaviour.

Another line of inquiry relates to thought processes captured during exercise performance. As featured in Chapter 2, cyclist’s thoughts predominantly related to active self-regulation (Whitehead et al., 2018), and therefore effortful control of thoughts, feelings and action to optimise pacing. Moreover, these self-regulatory efforts were more prominent in trained cyclists. Thus, whether an acquired or an inherent quality, conscious self-regulatory processes may underpin the superior pacing of trained athletes. Interestingly, TA and its possible interference in the self-regulatory resources it is used to capture was also assessed in Chapter 2. Although promising for TA use moving forward, why no reactivity was observed in measures of performance, perceptual experience and cognition remains unclear. A possible explanation could relate to reactivity effects through time pressure found in previous research (Fox et al., 2011) are different in nature to a ‘race against the clock’ of a cycling TT. For instance, a prefrontal dependent task with time pressure is taxing of prefrontal regions to the extent that it is performed slower with the burden of TA. In contrast, TT performance does not carry this cognitive burden and therefore the resultant reactivity effects. Thus, alongside Chapter 2, further explorations of methods to explore the self-regulation of endurance performance are much needed.

In summary, given the relationship between executive function and self-regulation, an exploration of how the former may underpin the latter within the confines of endurance performance may shed further light on our understanding of pacing.

Executive Function and Endurance Performance

Several studies have explored and found differences in executive function and cognitive capacities across different sports, such as ‘externally-paced’ and ‘self-paced’ sports (Ballester et al., 2019; Jacobson & Matthaeus, 2014), and ‘static’, ‘interceptive’ and ‘strategic’ sports (Krenn et al., 2018). Generally, this body of research has observed that athletes of externally-paced and strategic sports (e.g., team sports), compared to self-paced and static sports (e.g., long-distance running), tend to perform better on measures of executive function, particularly response inhibition. However, the categorization of sports as above could be confounding to the assessment of cognitive abilities across disciplines. For instance, triathlon is defined as a static sport by Krenn et al. (2018), characterised by “…mainly self-paced situations in highly consistent and stable circumstances” (p. 74). However, competitive triathlons require the ability to react to competitors (Williams et al., 2015) and optimally self-regulate pace to avoid neuromuscular failure (St. Clair Gibson et al., 2013). Therefore, the complex and dynamical processes of endurance sports (Renfree & Casado, 2018) are not adequately captured by such labels. Reinforcing this, Krenn et al. (2018) categorized triathlon with conceptually very different sports such as shooting and weightlifting, which are, respectively, fine and gross motor skill tasks without the pacing demands and competitor dynamics of endurance exercise sports.

Given the limitations highlighted above, this body of research may be underappreciating the contribution of self-regulatory skills to endurance performance. In addition, this research has not sought to investigate the cognitive capacities of endurance performers as a prime objective. However, one study by Cona et al. (2015) has investigated runner’s cognitive abilities and race performance. In this study, thirty ultra-marathon runners completed cognitive testing prior to an 80 km race. This testing involved detection (processing speed – testee responded to the presentation of a stimulus), go and no-go tasks (response inhibition – testee selectively responded to the presentation of a stimulus), a dual-task paradigm involving the completion of a two-back test (working memory – testee decided whether the current stimulus was the same stimulus presented two trials previous), whilst also remembering to respond to a pre-memorized stimulus (monitoring). Based on a median split of race performance, faster runners outperformed (i.e., mean accuracy) slower runners on the no-go task, but not the detect and go tasks. Reaction time to the pre-memorized stimulus was greater for slower runners during the two-back same condition (i.e., stimuli presented was the same as two trials previous), and even more so for emotional stimuli (i.e., [un]pleasant vs. neutral stimuli). Moreover, interference (i.e., increased reaction time) was greater for slower runners when the valence of the pre-memorized stimulus matched that of the two-back test. In short, faster runners appeared to have better inhibitory control, not only over motor responses, but also over interfering and distracting information. Importantly, this research provides preliminary evidence that executive function may be predictive of endurance performance. However, race performance was the only measure of ability assessed. Compounding this, the race in question was halted at the 30 km mark due to adverse weather conditions. In addition, analysis of pacing profiles would have provided an indication as to whether executive function capacities underlined superior performance through better optimized pacing.

Developmental research also provides evidence that highlights the role of executive functioning and cognitive mechanisms in the self-regulation of endurance performance. Micklewright et al. (2012) assessed the pacing behaviour of school children aged 5-14 years, and therefore at various stages of Piagetian cognitive development, completing a 150 m running task. This study showed that the ability of children to effectively regulate pacing develops with age. Younger children typically exhibited a negative pacing profile initiated by an ‘all-out’ approach, compared to older children who typically adopted a more conservative pacing approach. This suggests that younger schoolchildren’s ability to set an appropriate initial pace is limited by poor anticipation of running task demands. Interestingly, when controlling for age, pacing differences were associated with various stages of cognitive development. Specifically, the youngest schoolchildren in the lowest stage of cognitive development exhibited the most ineffective pacing strategies. Given that other developmental milestones appear critical to self-regulation (e.g., adolescent changes in executive functioning, Cohen-Gilbert & Thomas, 2013), and executive functions continue to develop into early adulthood (De Luca et al., 2003), future research exploring how cognitive development relates to the pacing of endurance performance is warranted. Following on, Van Biesen et al. (2016) compared the in-competition pacing of elite-level 400 m and 1500 m runners with and without intellectual impairment (intelligence quotient ≤ 75). Highlighting the critical role that cognitive functioning plays in pacing, runners with intellectual impairment displayed more variance in velocity fluctuations compared to runners without intellectual impairment, and when compared to the pacing profiles of world-record performances. This suggests that athletes with an intellectual impairment may find utilising metacognitive processes such as reactive control (Brick, MacIntyre, & Campbell, 2016) to optimise pacing more challenging.

As detailed in Chapter 1, research demonstrating adverse effects of mental fatigue to subsequent physical performance also points to a relationship between executive function and endurance performance (see Van Cutsem et al., 2017, for a review). In this review, studies typically compared the effects of a prolonged and cognitively demanding task, versus a less demanding task, on subsequent endurance performance. Interestingly, most of the cognitive tasks used captured self-regulatory processes or executive functions. The AX-continuous performance test adopted by eight of 11 studies measured self-regulation in line with the dual-mechanisms of control framework (Braver et al., 2007). Stroop tasks utilised by three studies are a prototypical measure of inhibition (Miyake et al., 2000) and typically involve responding in a timely fashion to word meaning or ink colour with conditions being congruent (e.g., ‘red’ displayed in red ink) or incongruent (e.g., ‘red’ displayed in blue ink). Van Cutsem et al. (2017) suggest that perception of effort plays a significant mediating role in the mental fatigue effects on endurance performance. Several theories to account for these effects have been provided. Of particular interest is the notion that extracellular concentration of adenosine (an endogenous nucleoside considered to be an inhibitor of neuronal activity) increases with neural activity (Lovatt et al., 2012). Moreover, adenosine accumulation within the brain of rats reduced exercise capacity (Davis et al., 2003). Pageaux et al., (2015) speculate that mental fatigue may induce adenosine accumulation in the pre-supplementary motor area and, saliently, the anterior cingulate cortex (ACC). The ACC is thought to be a ‘conduit’ between emotional experiences and executive functions (Mayberg et al., 2005), and is implicated in effortful cognitive control, as evidenced through activation of the area during incongruent Stroop task performance (Bush et al., 1998) and links to perception of effort (Williamson et al., 2001, 2002). Thus, perhaps the ACC plays a crucial role in maintaining executive functions to aid pacing, given the unpleasant emotions experienced that contribute to perception of effort during exercise.

A recent study by Martin et al. (2016) compared the effects of mental fatigue on endurance performance for ‘professional-’ and ‘recreational-level’ cyclists (Pauw et al., 2013). These cyclists completed a 30-minute incongruent Stroop task or a comparatively easier control task, which entailed sitting quietly in front of a computer screen and focusing on a black cross for 10 minutes. Participants were then challenged to cover as much distance as possible within 20 minutes on a cycle ergometer. Interestingly, Stroop task accuracy was superior among professional cyclists compared to their recreational counterparts. Unlike professional cyclists, TT performance among recreational cyclists was worse in the mental exertion condition than in the control condition, as evidenced by a decrease in speed, power output and distance covered. The authors purported that Stroop performance was indicative of better inhibitory control in professional compared to recreational cyclists. In corroboration with Cona et al.’s (2015) findings, the results suggest that superior inhibitory control is a psychobiological characteristic of successful endurance athletes. To test the hypothesis that resistance to fatigue is trainable, recent research has investigated the benefit of a physical endurance training program to improve resistance to mental fatigue among an untrained but healthy population (Filipas et al., 2020). The researchers observed an improvement in TT performance (i.e., distance covered within 15 minutes) and power output relative to RPE for those completing an endurance training program (i.e., 12 sessions across 4 weeks) relative to a control group (i.e., documentary watching) following the inducement of mental exertion (i.e., 90-minute cognitive battery). However, given that no significant changes in cognitive parameters or perceived mental and physical demand were observed post-intervention, to what extent improvements observed reflect central adaptions or merely an increase in cardio-respiratory fitness is unknown (de Lima-Junior et al., 2021).

From an applied perspective, research has highlighted the possible benefits of inhibitory control to endurance performance. Both involuntary distraction and awareness of internal physiological states during exercise are associated with inefficient pacing and movement economy, when compared to more active self-regulatory cognitions (e.g., on technique; Brick et al., 2014). In addition, over processing of pain and discomfort has been associated with elevated perceptions of exertion (St. Clair Gibson et al., 2006). Therefore, superior inhibitory control may support self-regulatory attentional focus during challenging levels of exertion. Furthermore, it is likely that inhibitory control capacity becomes increasingly important during endurance tasks, given that sensations of physical discomfort become more salient with increasing intensities (Balagué et al., 2012). In summary, it is proposed that executive functioning supports effective self-regulatory cognition to aid endurance performance through its dual support of goal-directed attention and inhibition of attentional resources toward task-irrelevant stimuli. Ultimately, these functions keep conscious attention focused on goal-relevant information and free from information incompatible with the desired goal (e.g., pain and discomfort).

Executive Function, Exercise and the Brain

The reciprocal relationship between cognitive function and exercise means that whilst decision-making impacts effort regulation, exercise itself impacts cognition in numerous ways. Moderate intensity exercise enhances cognitive processing (Brisswalter et al., 2002), yet executive functioning, particularly for more complex, interference control, has been observed to compromise attentional resources that are required for large-scale bodily movements inherent in exercise

(Pontifex & Hillman, 2007). The effects of exercise on cerebral haemodynamics provides neurological evidence for the implication of executive functions in the self-regulation of endurance performance. A systematic review by Rooks et al. (2010) considered the effects of incremental exercise on cerebral oxygenation as measured by functional near-infrared spectroscopy (fNIRS). This technology uses near-infrared light to measure cerebral haemodynamics by assessing the absorption spectra of oxyhaemoglobin (O_2Hb) and deoxyhaemoglobin (HHb). fNIRS provides acceptable spatial resolution (~1 cm) and is more tolerant to movement artefacts than other measures (Rooks et al., 2010). Several key findings of the review are worthy of our attention. To begin with, PFC O_2Hb changed as a function of exercise intensity and followed a quadratic trend. Oxygenation initially increased between low and moderate intensities, remained stable from moderate-to-hard intensities, and then declined at maximal, exhaustive intensities. Oxygenation also differed as a function of training status: aerobically trained participants obtained higher absolute O_2Hb, HHb and cerebral blood volume as approximated by total haemoglobin (tHb). Among untrained participants, relative to their aerobically trained counterparts, a marked drop in O_2Hb and a small increase in HHb accompanied declines in tHb.

Given the importance of executive function to the self-regulation of endurance performance, of particular interest are studies that have investigated cerebral activity during self-paced, aerobic exercise performance. Two studies have investigated PFC haemodynamics during a full-effort 5 km treadmill run in both trained (Billaut et al., 2010) and elite-level Kenyan runners (Santos-Concejero et al., 2015). In both studies, O_2Hb and HHb increased across the first 2.5 km. However, oxygenation levels remained stable for elite level runners, whereas O_2Hb decreased and HHb increased during the last 500 m among well-trained athletes. This suggests that some homeostatic disturbance is tolerated during high-intensity exercise. The stabilisation of measures for elite runners possibly relates to cerebrovascular remodelling to preserve cerebral oxygenation in those born at high altitude. Building on this work, research has explored the purpose of such cerebral changes during exercise.

The reticular activating hypofrontality (RAH) model (Dietrich & Audiffren, 2011) postulates specific neurological phenomena concerning PFC haemodynamics during exercise. The model works on the premise that whole-body dynamic exercise is metabolically costly and neural processing that requires the brain's limited metabolic resources continually occurs on a competitive basis. As a result, there is a compensatory and transient downregulation in brain areas involved in higher-order cognition (i.e., PFC) to brain regions more important for the control of movement: motor, sensory and autonomic areas. In addition, the greater the duration, and to a lesser extent, intensity of exercise, the greater the hypofrontality effect. Due to this hypofrontality, the model predicts that cognitive processes (i.e., top-down, goal-driven processes) synonymous with executive function will be compromised during exercise, as will self-regulatory processes that are key to pacing. To support the model, Dietrich and Audiffren (2011) point to the exclusive impairment of performance during exercise on cognitive tasks requiring explicit processing, as opposed to implicit processing, or tasks requiring both. For instance, 45 minutes of cycling or running at 75% of maximum heart rate resulted in worse performance on the Wisconsin card sorting task (a measure of prefrontal dependent cognition), but not on the brief Kaufman intelligence test (a measure of general cognition; Dietrich & Sparling, 2004). However, the RAH model and Rooks et al.'s (2010) findings are not in full agreement, with evidence of a hypofrontality effect only occurring at maximal, exhaustive intensities. Beyond Rook et al.'s (2010) review, research conducted to investigate cerebral haemodynamics, exercise and executive functions has provided varied findings and mixed support for the RAH model.

Santos-Concejero et al., 2017) tasked elite Kenyan runners to complete a training session that consisted of 1 km bouts at 5% faster than their average 5-km pace with 30 second recovery periods until volitional exhaustion. Left PFC O_2Hb measured at the end of each bout progressively declined over the training session. O_2Hb was higher during rest periods but also showed a progressive decline. The data was split to separate runners completing five or fewer bouts (i.e., early fatigue group) from those completing six or more (i.e., late fatigue group). Interestingly, O_2Hb decreased less between bouts in the late fatigue group. The findings suggest that superior runners can better defend against decreases in cerebral oxygenation during self-paced exercise, providing a tangible link between endurance performance success and PFC O_2Hb. Another study conducted by Sudo et al. (2017) required 32 healthy males to complete a spatial delayed response (a measure of working memory) and a go no-go task pre and post an incremental cycle ergometer test or a rest period. The degree of PFC cerebral oxygenation was associated with reaction time on the cognitive tasks post-exercise. The two measures were negatively correlated as cerebral oxygenation increased and reaction time shortened (i.e., improved). The present findings suggest that the maintenance and recovery of cerebral oxygenation are key determinants of cognitive performance in sports under exhaustive conditions. Thus, both studies show partial support for the RAH model (as cerebral haemodynamics were not measured over the motor cortex) and highlight the reciprocal relationship between the brain, exercise characteristics and their regulation.

Radel et al. (2017) have recently suggested a refinement to the RAH model. Research has observed a causal link between the central executive network, including the right dorsolateral PFC responsible for attentional control, and the default mode network, including the right medial PFC responsible for mind-wandering states (Dosenbach et al., 2006). In Radel et al.'s (2017) research, physically active participants were asked to cycle at 60% peak aerobic power for either 10 or 60 minutes. However, the test was always terminated after 10 minutes. Right dorsolateral PFC O_2Hb was greater when participants anticipated exercising for 10 versus 60 minutes; the opposite was true for the right medial PFC. Participant's focus was less on the trial in the 60- versus 10-minute trial and right dorsolateral PFC O_2Hb positively correlated with self-reported focus on the task. Although distraction from an exercise task can be detrimental to performance (Connolly & Janelle, 2003), whether the reduced task focus observed represents active or passive distraction is unclear. Firstly, the authors assume that hypofrontality resulted from a strategic conservation of mental effort resources. As such, Radel et al. (2017) believe that if any part of the PFC is downregulated during exercise, it is the regions involved in the central executive network (i.e., the right dorsolateral PFC), as they support relatively costly functions and cannot be maintained for extended periods. Pertinently, these are the functions proposed to be most beneficial to the effective regulation of endurance performance (Brick, MacIntyre, & Campbell, 2016).

Despite the above findings, other research has demonstrated a *hyper*frontality, as opposed to a hypofrontality effect. Research by Tempest et al. (2017) required 14 physically active participants to complete 60 minutes of cycling at 10% above their ventilatory threshold and at 30 Watts in a cross-over design. During cycling, participants completed 10 blocks of a two-back task, flanker task (response inhibition) and rest period (all 2 minutes in duration). High- versus low-intensity exercise shortened reaction time in the flanker task but impaired performance in the two-back task. These findings show a potential deleterious effect of high-intensity exercise on executive control. Right PFC O_2Hb increased from blocks 1-3 in the high-intensity condition, then stabilised through to block 10; whilst right motor cortex O_2Hb remained stable across all 10 blocks. Given the implications of compromised cognitive control for self-regulation of effort, these effects warrant further exploration in self-paced exercise alongside prescribed intensities. Whilst the findings contradict the RAH model, the lack of PFC O_2Hb decline over time during high-intensity exercise may be attributable to the engagement of executive functioning. This suggests that active-self-regulatory processes can be engaged during effortful activity. Addressing post-exercise effects, Faulkner et al. (2016) tasked physically active participants with cycling at 45-60% of their VO_{2max} on an upright and recumbent cycle ergometer. Post-exercise improvements in Stroop task completion time were observed in both exercise tasks and was associated with higher regional oxygen saturation (i.e., tissue saturation index) in the PFC. The findings provide an indication that moderate-intensity aerobic activity improves executive function acutely post-exercise (by 4-7%). Given these equivocal findings, further research is required to elucidate the neurophysiological impact of exercise on the PFC, its respective areas, and executive functioning. Moreover, investigations into the conditions (e.g., the nature of exercise, executive functions examined, participants characteristics etc.) that may mediate this relationship are also required.

Alongside hypofrontality, laterality and the respective functions of the left and right PFC should also be considered. Concerning negative affect, the right PFC has been theorized to relate to avoidance-based emotion (e.g., anxiety) and the left PFC to approach-based emotion (e.g., anger; Davidson, 2002). As conceptualized by Ekkekakis (2009) and more recently Bigliassi and Filho (2022), it is possible that the PFC may influence decision-making during exercise by regulating this approach-avoidance dynamic. Specifically, the right PFC functions to inhibit the amygdala (i.e., fear, threat detection) to suppress negative affect in the face of aversive stimuli (e.g., exercised-induced somatic cues), allowing an athlete to persist with exercise under challenging circumstances. Empirical evidence for this specificity of the PFC during exercise is limited. However, using fNIRS, Subudhi et al. (2009) observed larger increases in oxygenation in the right compared to left PFC at volitional exhaustion. This would seem teleologically plausible until a level of homeostatic disturbance would be damaging, whereby inhibition from the PFC would desist, allowing interceptive afferents to dominate conscious awareness, leading to a lowering of work rate or termination of exercise. However, as little is known about PFC asymmetries during exercise performance, ambitious projects using multi-channel fNIRS systems to measure several bilateral brain regions (e.g., prefrontal and motor regions) are needed to explore the specific functions of the PFC in self-regulating performance.

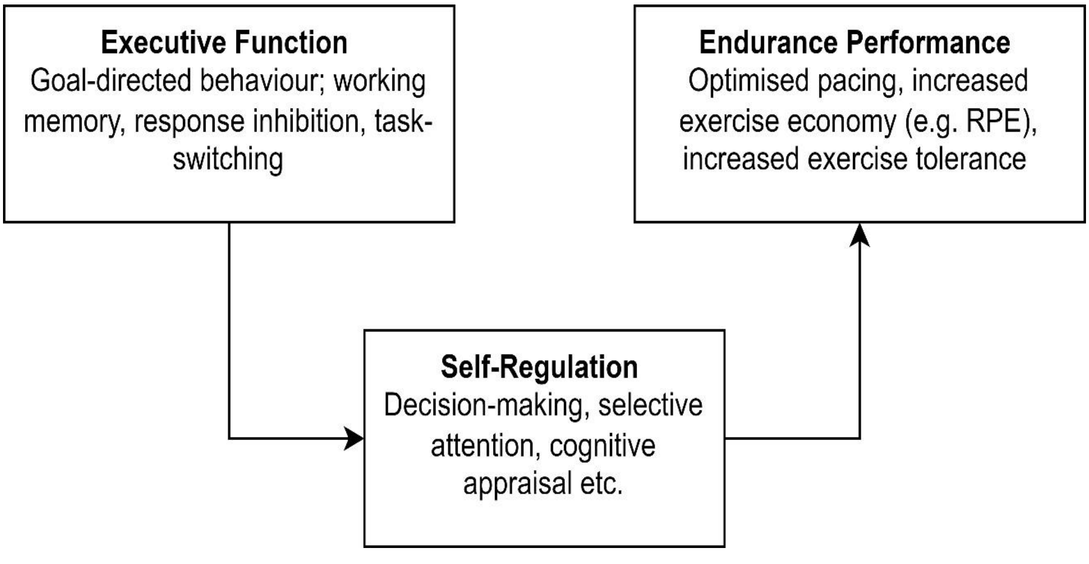
Moving on, if executive function is important to the self-regulation of endurance performance as described above, is it possible to ‘boost’ executive functioning to aid decision-making and pacing during effortful exertion by using cognitive strategies? Tempest and Parfitt (2013) investigated the effect of imagery on affective response and PFC haemodynamics during exercise. Physically active participants employed energy- and enjoyment-focused imagery during an incremental cycling test to exhaustion. At intensities above the ventilatory threshold, dorsolateral PFC HHb was higher and O_2Hb lower in the imagery versus control condition, indicating greater dorsolateral PFC activity (i.e., oxygen utilisation). Below the ventilatory threshold, cognitive factors are thought to largely determine affective response; above the ventilatory threshold, interoceptive cues become more salient as workload intensity becomes more difficult to maintain (Ekkekakis, 2005). Thus, imagery may serve to engage the dorsolateral PFC and maintain cognitive dominance around and above the ventilatory threshold, aiding self-regulation during high-intensity exercise associated with greater threat from interoceptive cues. Moving on, Wallace et al. (2017) conducted a novel investigation into the effectiveness of motivational self-talk on constant-load cycling, time to exhaustion and cognitive function among trained athletes in the heat. Only motivational self-talk significantly improved time to exhaustion (29% increase) and this was coupled with an ability to maintain near maximal self-reported exertion for significantly longer (100% increase). In addition, motivational self-talk led to a significant improvement in both the speed and accuracy of the Groton maze learning task (a measure of error detection and spatial memory) during rest periods between the exercise tasks. Thus, motivational self-talk may influence the appraisal of exertion related to physical exercise and improve executive function when exercising in the heat. Motivational self-talk may also impact relevant areas of the brain (e.g., the anterior insular cortex and ACC) implicated in the appraisal of afferent homeostatic signals to determine perceptions of bodily state (e.g., thermo-physiological strain; Paulus et al., 2009) and executive function (Robertson & Marino, 2016), ultimately mitigating the volitional termination of exercise. Although the evidence is limited to-date, these studies suggest that the employment of active cognitive strategies during challenging exertion can support executive function through changes in associated brain regions that may have important implications for the ability to effectively regulate effort.

Following on from Martin et al.'s (2016) findings mentioned previously, the authors speculate on the extent to which inhibitory control is an inherited or acquired ability. Twin studies suggest that executive functions are one of the most inheritable psychological traits (Friedman et al., 2008). Nonetheless, endurance athletes likely exercise inhibitory control on a more regular basis than the general population (e.g., strict adherence to dietary and training regimens), potentially strengthening their inhibitory control. Indeed, students who completed self-control exercises demonstrated greater self-regulatory capacity on a handgrip endurance task following a thought suppression task requiring inhibitory control (Muraven et al., 1999). Thus, future research should look to establish whether executive functions themselves are trainable, and the impact this may have on endurance performance. Preliminary findings highlighted that 12 weeks of regular endurance training coupled with the completion of a mentally fatiguing task (the AX-continuous performance test) improved cycling time to exhaustion, relative to endurance training alone (Marcora et al., 2015). Transcranial direct current stimulation (tDCS) has also shown promise as an ergogenic aid to improve endurance performance. tDCS is a non-invasive method to stimulate the brain and increase cortical excitability (Nitsche & Paulus, 2000). A review conducted by Machado et al. (2019) featured two studies using tCDS over the dorsolateral PFC; one study showed an improvement in time to exhaustion completed at peak aerobic power (Lattari et al., 2018), while the other showed no improvement in 20-minute cycling TT performance (Holgado et al., 2019) versus control (i.e., sham tDCS) conditions. Whilst these explorations are nascent at present, it is plausible that tDCS can enhance executive control to increase exercise tolerance under high-workload, however further research is required.

Conclusion and Future Directions

In summary, Figure 3.1 contains several key propositions from the present review. Firstly, whole-body exercise impacts on executive function and associated brain areas, as evident in performance on prefrontal-dependent tasks (Dietrich & Audiffren, 2011) and PFC cerebral haemodynamics (Rooks et al., 2010) during exercise. There is also evidence to suggest that psychological interventions (e.g., Tempest & Parfitt, 2013), training executive functions (e.g., Marcora et al., 2015) and tDCS (e.g., Lattari et al., 2018) can potentially 'boost' executive functioning to aid endurance performance. Secondly, executive function would appear to underpin self-regulation (Hofmann et al., 2012) and is intricately linked to meta-cognitive processes (Roebers, 2017). As a result, the authors propose that self-regulation is crucial to endurance performance and that executive function may underpin the top-down self-regulatory processes involved. Indeed, baseline executive functioning capacity has explained subsequent differences in endurance performance (e.g., Cona et al., 2015). As such, challenges to, or deficits in executive functioning would have potentially negative implications for exercise tolerance, and the pacing and decision-making required for optimal endurance performance.

Figure 3.1 Executive Function, Self-Regulation and Endurance Performance.



Executive Function
Goal-directed behaviour; working memory, response inhibition, task-switching

Endurance Performance
Optimised pacing, increased exercise economy (e.g. RPE), increased exercise tolerance

Self-Regulation
Decision-making, selective attention, cognitive appraisal etc.

Given the recent implication of executive functions in endurance performance, there is plenty of scope for future research. Assessment of PFC haemodynamics could provide greater validity to contemporary findings and theories in exercise science. For instance, with respect to Brick et al.'s (2014) metacognitive framework, are there PFC activity differences when reactive versus proactive control is adopted? In addition, is PFC activity different between trained versus untrained athletes, and is this a reflection of reported focus (i.e., active self-regulation vs. involuntary distraction)? Following on, are PFC changes during endurance performance following mental fatigue induced by prefrontal task dependent engagement (Van Cutsem et al., 2017)? Indeed, the mental fatigue literature has been cited as key evidence to support the psychobiological model of endurance performance (Pageaux et al., 2014). Building on Tempest and Parfitt's (2013) work, there is scope for further research to investigate whether engagement of executive functions may be a mechanism by which psychological interventions improve endurance performance. For instance, assessment of PFC haemodynamics would add weight to and build on research showing benefits to both performance and cognition through motivational self-talk (Wallace et al., 2017). Moreover, there is sufficient findings to warrant further investigations into the engagement of executive functions via PFC tDCS (e.g., Machado et al., 2019), the trainability of executive functions via prefrontal dependent task practice (e.g., Marcora et al., 2015), and the transferability of these effects to endurance performance. However, this future research will need building on sound methodological foundations. This is especially pertinent where this concerns the adoption of relatively new and complex technologies, such as fNIRS. In Chapter 4, literature concerning fNIRS assessment of cerebral haemodynamics during self-paced endurance performance will be under scrutiny, with both the methodology itself and the findings from reviewed studies subject to critique.

Chapter 4 Self-Paced Endurance Performance and Cerebral Haemodynamics of the Prefrontal Cortex: A Scoping Review of fNIRS Methodology and Findings

Parts of this chapter have been published in a peer-reviewed journal.

Hyland-Monks, R., Marchant, D., & Cronin, L. (2022). Self-Paced Endurance Performance and Cerebral Hemodynamics of the Prefrontal Cortex: A Scoping Review of Methodology and Findings. *Perceptual and Motor Skills*, *129*(4), 1089-1114. https://doi.org/10.1177/00315125221101017

Abstract

Recent research has suggested that top-down executive function associated with the prefrontal cortex is key to self-regulation and feedback decision-making in pacing endurance performance. A small but growing literature has investigated the neurological underpinnings of these processes by subjecting the prefrontal cortex to functional near-infrared spectroscopy (fNIRS) measurement during self-paced endurance task performance. Since fNIRS measurement for these purposes is a recent development, the principal aim in this review was to assess fNIRS methodological rigor and findings. Promisingly, in 17 studies that met the criteria for inclusion, most had adopted commonplace and feasible best practice guidelines. However, non-adherence to some guidelines included failure to implement measures to remove artefacts from data. These studies revealed the significance of cerebral oxygenation in endurance performance and the specific role of the prefrontal cortex in pacing behaviour. Future research should more closely follow best practice guidelines and focus on the role of the brain to develop techniques for improving or maintaining PFC oxygenation in endurance performance.

Introduction

Chapter 3 outlined how self-regulation is crucial to the decision-making processes and pacing of endurance exercise performance (Hyland-Monks et al., 2018). The review conducted by Hyland-Monks and colleagues draws upon various research domains to argue that executive function, predominantly governed by the prefrontal cortex (PFC), underlies the top-down self-regulation of endurance performance. Although executive function *per se* is not explicitly referenced, contemporary thinking concerning the psychology of endurance performance places self-regulatory processes at centre stage. For instance, Brick et al. (2014) argue that metacognitive skills (i.e., planning and monitoring) and experiences (i.e., feeling and judgements) are key to the regulation of endurance performance. Providing a foundation for this work, Roebers (2017) presented a unified account of self-regulation by synthesizing the scientific understanding of executive function and metacognition. Furthermore, Marcora's (2010) psychobiological model proposed that the conscious regulation of pace is governed by the integration of potential motivation and effort perception. Perceived exertion, motivational drive, and potential modifiers of these variables (e.g., self-talk; Barwood et al., 2015) may be information that is, in part, integrated by the PFC to inform decision-making regarding pace (Robertson & Marino, 2016).

Following on, researchers have theorized that an evolutionary-driven trade-off in efficiency impacts brain activity during exercise. The reticular activating hypofrontality (RAH) model (Dietrich & Audiffren, 2011) proposes that exercise induces a hypofrontality effect. As whole-body dynamic exercise is metabolically costly, the limited resources of the brain are preserved for areas implicated in the control of movement (i.e., motor and sensory areas; Christensen et al., 2000), resulting in a downregulation in the PFC with associated costs to EF. This hypofrontality effect is thought to increase in line with exercise duration and intensity. Therefore, based on the RAH model propositions, the downregulation of the ‘hardware’ to self-regulate during exercise presents a challenge to endurance performers concerning the top-down control of pacing. This has possible implications for the ability to integrate performance feedback by the PFC. Experimental (Wingfield et al., 2018) and field-based (Dukalski et al., 2020) research has demonstrated that the removal of live performance feedback hinders cycling time-trial (TT) performance and pacing. Interestingly, when feedback was provided, power output was strongly associated with PFC activity (Wingfield et al., 2018). This ability to integrate performance feedback may also explain differences in performance. Faster finishers in an ultramarathon displayed superior executive function capacities (Cona et al., 2015). Likewise, more experienced cyclists were less susceptible to mental fatigue (induced through executive function testing) in subsequent TT performance (Martin et al., 2016).

Given the above, researchers have sought to investigate the PFC and its potential role in endurance performance using functional near-infrared spectroscopy (fNIRS). fNIRS is a non-invasive method reliant on near-infrared light (between 650–900 nm) to measure cerebral haemodynamics by assessing the absorption spectra of oxyhaemoglobin (O_2Hb) and deoxyhaemoglobin (HHb) reflections from cortical tissue (Villringer et al., 1993). fNIRS relies on neurovascular coupling (Filosa & Blanco, 2007), whereby an increase in energy consumption from an active brain region increases cerebral blood flow to the area to supply oxygen and nutrients. As oxygenation outstrips demand, blood oxygenation levels rise in the brain area in question. This interplay between O_2Hb and HHb forms the basis by which fNIRS methodology allows inference regarding cortical activity from neurovascular redistribution. fNIRS is used within exercise research because the technology is relatively robust to movement artefacts and offers acceptable spatial resolution in comparison to other available neuroimaging methods (Perrey, 2008).

A systematic review of cerebral oxygenation (Cox) during incremental exercise found that oxygenation in the PFC typically increases between low and moderate exercise intensities, remains stable from moderate-to-hard intensities, and decreases when nearing exhaustion (Rooks et al., 2010). At very hard intensities, compared to their less trained counterparts, aerobically trained participants obtained higher absolute values of O_2Hb, HHb and cerebral blood volume, as approximated by total haemoglobin (tHb). Further research has also focused on cerebral haemodynamics to shed light on the psychology of endurance performance. Investigators have observed changes in PFC activity as a function of exercise intensity and cognitive load (Tempest et al., 2017), deception regarding exercise duration (Radel et al., 2017) and using imagery to aid performance (Tempest & Parfitt, 2013). However, these investigators adopted methodologies that featured prescribed exercise intensities. Therefore, self-paced protocols are also needed to gain insight into the self-regulation of endurance performance via brain-based executive processes.

A small and growing cohort of researchers are interested in self-paced endurance performance and the cerebral haemodynamics implicated in EF. This work has included exploratory investigations of PFC oxygenation during full-effort treadmill TT running in trained (Billaut et al., 2010) and elite (Santos-Concejero et al., 2015) athletes. Several studies have investigated simulated altitude effects (i.e., hypoxia) on PFC haemodynamics during self-paced endurance performance (Bourdillon et al., 2014; Fan et al., 2013; Ferguson et al., 2018; Hamlin et al., 2010; Nielsen et al., 1999), while others have investigated the potential for ergogenic aids to ameliorate hypoxic effects or increase cerebral perfusion (Decroix et al., 2016, 2018; Fan et al., 2018; Liao et al., 2019; Shannon et al., 2017; Shaw et al., 2020). In addition, new research has provided insight into the effect of feedback blinding (Wingfield et al., 2018) and distance deception (Wingfield et al., 2019) on PFC oxygenation during cycling TT performance.

The methodology for self-paced protocols used in the studies mentioned above presents several challenges for fNIRS measurement of the brain. Most pertinent is the high-intensity effort performed around and above the ventilatory threshold (Goldberg et al., 1988). Although most athletes distribute their resources to avoid complete catastrophic failure and collapse (St. Clair Gibson et al., 2013), the strain of high-intensity exercise results in biomechanical changes in motor performance, for instance, at the hip and knee joint during cycling (Bini et al., 2010). This likely has implications for whole-body movement, as evident in the ‘swaying’ of the upper body observed in cyclists when fatigued. This creates the potential for movement artefacts in addition to those presented by lower intensity exercise. Although analytic techniques may mitigate the effect of artefacts, they still present a possible confounding effect by reducing the signal-to-noise ratio (Pinti et al., 2019). A second challenge relates to experimental control. Many protocols using fNIRS for exercise-based research have adopted block or event-related designs (Herold et al., 2018), allowing researchers to relate cortical haemodynamics to discrete events (e.g., assessment at various prescribed exercise intensities). Although experimental manipulations can be used in self-paced protocols, participants are typically free to pace activities as they wish, giving added importance to how researchers analyse fNIRS data to compare experimental conditions (e.g., recording windows). To date, however, there have been no extensive efforts to specifically review this body of research and the unique challenges it presents.

Several recent efforts have been made to review both the methodology and findings of exercise-based research using fNIRS to assess cortical haemodynamics. Perrey and Besson (2018) compared this methodology to other neuroimaging methods and highlighted attempts at using fNIRS to answer longstanding unknowns regarding exercise physiology and neurological phenomena (e.g., acute and long-standing effects of exercise on the brain). Herold et al. (2018) systematically reviewed the methodological rigor of studies using fNIRS to investigate cerebral haemodynamics, cognition and exercise. Most recently, De Wachter et al. (2021) reviewed the literature on endurance performance and PFC oxygenation, organizing their findings by the nature of the exercise completed (i.e., intensity). However, this review only featured three of the studies included in the present review. Although touched upon in Chapter 3, no review has primarily focused on studies using fNIRS during self-paced endurance performance. The aim of this review was to assess both the methodology and findings of investigations using fNIRS to study the relationship between cortical haemodynamics of the PFC and self-paced endurance performance. More specifically, the review sought to establish best practice evidence for fNIRS use and the adherence of reviewed studies to these guidelines, and to provide a theoretical and practical commentary on study findings to date.

Method

To ensure robustness and adherence to discipline standards, where appropriate, the researcher followed the guidelines provided by the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) pertaining to scoping reviews (Tricco et al., 2018). To ensure transparency, the review was preregistered on the Open Science Framework website (DOI: 10.17605/OSF.IO/7XDBJ).

Search Process and Criteria

In November 2021, the researcher performed a systematic literature search across two electronic databases (PsychINFO and SPORTDiscus) to identify relevant studies using the following criteria: (i) Inclusion of at least one self-paced, full-effort performance-focused endurance exercise task, defined as whole-body, dynamic exercise that involved continuous effort and lasted for 75 seconds or longer (McCormick et al., 2019), and (ii) Use of fNIRS to assess cortical haemodynamics over any area of the PFC during exercise. Searches were restricted to article titles of studies published in English language only. As fNIRS use in human research began in the early 1990s (Ferrari & Quaresima, 2012), the search process was also restricted to articles published between 1990-present. For SPORTDiscus, the search was further restricted to journal articles with abstracts available. For PsychINFO, the search was restricted to articles using human participants aged 18+ years. The following search strings were used in both databases:

> aerobic OR cycli* OR endurance OR exercis* OR pace OR pacing OR physical activity OR run* OR time trial* OR time-trial* OR training
>
> AND
>
> cerebral OR cortical OR fNIRS OR functional near-infrared spectroscopy OR near-infrared spectroscopy OR neural OR NIRS OR oxygenation OR PFC OR prefrontal cortex
>
> NOT
>
> cerebral palsy[1]

All articles derived from the search strategy described above were databased in Mendeley Desktop (v1.19.8). To remove any duplicates, a ‘check for duplicates’ was performed within the software. The study criteria described above was used to conduct a careful review of the articles’ titles, abstracts, and keywords. Articles that fell unambiguously outside these criteria at this stage were excluded. The remaining articles were then subject to full-text review against the study criteria. A reason for any articles excluded from review at this stage was provided. The references and citations of articles that reached the full-text review stage were then screened. Any of

---

[1] Cerebral palsy was included as an exclusory term as it was a prevalent ‘subject’ in pilot searches of the SPORTDiscus database and unlikely to capture research of interest to the review.

these articles that met the study criteria were then also subject to full-text review. Figure 4.1 outlines this search process and Table 4.1 outlines the inclusion criteria.

Figure 4.1 Flowchart Detailing the Selection Process.

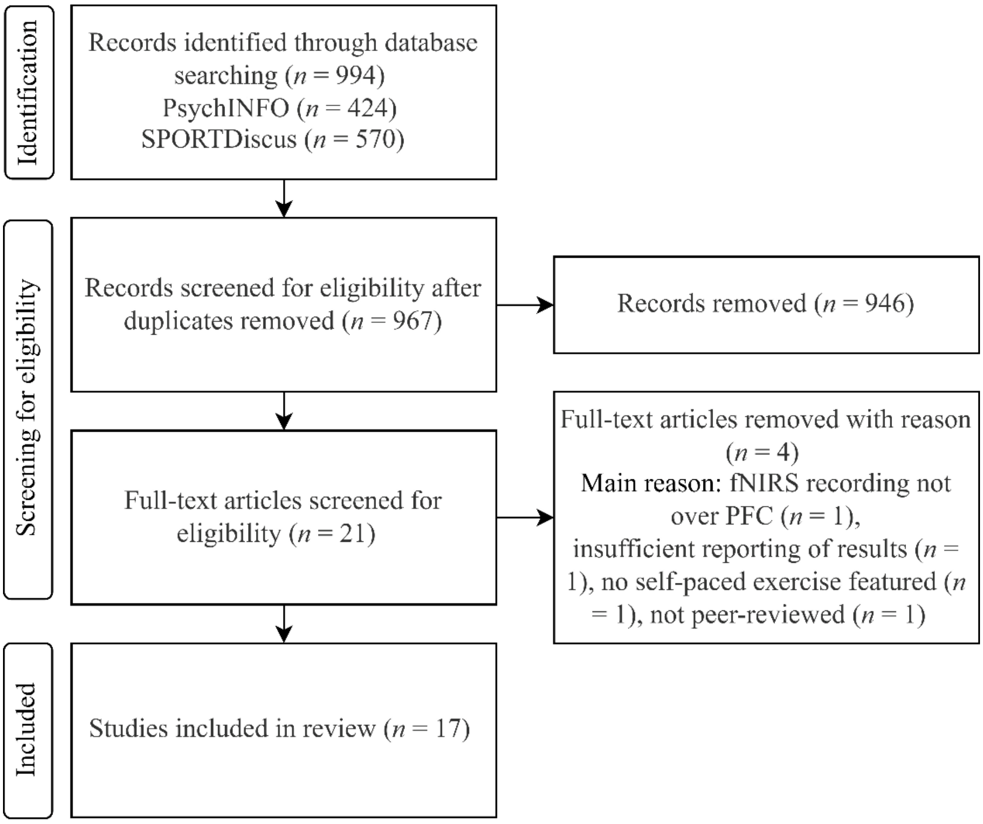


Table 4.1 Study Criteria for Review Inclusion.

Study criteria
i. Published in a peer-reviewed journal.
ii. Published in English language.
iii. Published between 1990-present.
iv. Healthy participants aged 18+ years who were not defined as a clinical population.
v. fNIRS measurement of the PFC during full-effort self-paced endurance performance (defined as whole-body dynamic exercise lasting ≥ 75 seconds).
vi. Clear reporting of research methods, participants, measures, and outcomes.

Note. fNIRS = functional near-infrared spectroscopy, PFC = prefrontal cortex.

Data Extraction

Following the full-text review stage, 17 studies were found to meet the study criteria. The following information was extracted from these studies: study authorship and year of publication; sample characteristics, including sample size, gender, and proxies of cardiorespiratory fitness level; key elements of study methodology and findings. Concerning fNIRS, the following information was extracted: brain region of interest (ROI); fNIRS recording methods, including methods of optode placement, source-detector separation distance and baseline recording protocols; data processing and methods of analysis, including differential pathlength factor (DPF) determination, artefact removal methods and data analysis techniques.

Results and Discussion

This section features the key methodological considerations for fNIRS recording, data processing and data analysis for exercise-based research. First, the importance of each consideration is stressed, and then an outline of how the reviewed studies approached each consideration is presented. The reviewed studies are compared to what has now been determined in relation to methodological rigor in the broader context of exercise-based research. Table 4.2 outlines best practice recommendations derived from both exercise-based research (e.g., Herold et al., 2018) and broader methodological reviews of fNIRS quality control (e.g., Orihuela-Espina et al., 2010). Table 4.2 also features the adherence of reviewed studies to these recommendations.

Table 4.2 Best Practice Recommendations for use of fNIRS for Cerebral Measurement and Number of Reviewed Studies that Adhered to These Recommendations.

	Key recommendations	**Study adherence**
fNIRS recording		
Positioning & securing optodes	Optimal: Co-registration via fMRI[a] or 3-D digitizer[a].	None
	Acceptable: Use of 10-20 EEG international system.	10 studies
	Use of placeholder, headband, or adhesive tape to secure position.	13 studies
Source-detector separation	Appropriate inter-optode distance range for adults: 3-5 cm.	15 studies
Baseline	Position reflects the postural demands of the exercise task.	15 studies
	No optimal length established but should be appropriate to research design.	N/A[b]

	Observation of fNIRS channel traces for good SNR (i.e., pulsation).	None
Data processing & analysis		
DPF	Optimal: Direct quantification of DPF values[a].	None
	Acceptable: Use of age-dependent formula.	6 studies
Artefacts	General artefact removal through use of appropriate set cut-off frequencies (i.e., bandpass filter).	1 study
	Physiological and motion artefact removal through sophisticated methods (e.g., principal component analysis).	None
Data analysis	Where appropriate, baseline correction to data performed.	All studies
	Analysis to include O_2Hb and HHb at minimum.	15 studies
	Measurement windows for averaging data should be appropriate to research design.	N/A[b]

Note. Adherence was inferred from sufficient reference to procedures in a full-text review. DPF = differential pathlength factor, EEG = electroencephalographic, fMRI = functional magnetic resonance imaging, fNIRS = functional near-infrared spectroscopy, HHb = deoxyhaemoglobin, O_2Hb = oxyhaemoglobin, SNR = signal-to-noise ratio.

[a]Rarely adopted approach in exercise-based research.

[b]Judgment is reserved as a subjective decision by researchers made in line with research design.

Positioning and Securing Optodes

Accurate and reliable positioning of optodes is crucial to allow for data recording from the ROI to make sound comparisons within and between participants. The gold standard for optode positioning is co-registration with magnetic resonance anatomical data (Orihuela-Espina et al., 2010). This is a costly procedure and therefore unlikely to be available to most investigators in sport and exercise science laboratories. Newer methods allow for the personalization of optode positioning by using measurements from a 3D digitizer (Fekete et al., 2011). However. this method has yet to become common practice, not least in sport science. The 10-20 electroencephalographic (EEG) system is typically used for optode positioning in sport and exercise research adopting fNIRS (Herold et al., 2018). Ten of the reviewed studies used the 10-20 EEG system for optode placement (Billaut et al., 2010; Bourdillon et al., 2014; Decroix et al., 2016, 2018; Liao et al., 2019; Pires et al., 2016; Robertson et al., 2016; Santos-Concejero et al., 2015; Wingfield et al., 2018, 2019). Seven studies made anatomical references to the PFC (i.e., forehead) but used no recognized system (Fan et al., 2013, 2018; Ferguson et al., 2018; Hamlin et al., 2010; Nielsen et al., 1999; Shannon et al., 2017; Shaw et al., 2020). Therefore, the reviewed studies partially reflect trends seen in the broader exercise-based literature.

Several methods were adopted by the reviewed studies to mitigate the impact of optode movement and to block extraneous light. These are especially important measures in respect to whole-body dynamic exercise which increases the risk of optode movement. These included securing optodes in some form of placeholder by black tape or adhesive discs (Billaut et al., 2010; Decroix et al., 2016, 2018; Ferguson et al., 2018; Hamlin et al., 2010; Nielsen et al., 1999; Pires et al., 2016; Robertson et al., 2016; Santos-Concejero et al., 2015; Shannon et al., 2017; Wingfield et al., 2018, 2019), and coverage of optodes with a dark headband or material (Billaut et al., 2010; Decroix et al., 2016, 2018; Robertson et al., 2016; Santos-Concejero et al., 2015; Shaw et al., 2020). These measures are important for ensuring good optode-skin coupling, limiting ambient light reaching detectors, reducing the prospect of optode movement artefacts, and improving the wearer’s comfort (Orihuela-Espina et al., 2010).

Source-Detector Separation

Establishing the optimal source-detector separation is an important consideration. This is because a shorter distance results in signals originating from extra-cerebral structures and a longer distance (∼45 mm and above) results in reduced signal quality as little light reaches the detectors (Orihuela-Espina et al., 2010). The majority of exercise-based research has used a 30 mm distance (Herold et al., 2018). A variety of source-detector separations were adopted by the reviewed studies, ranging from 30 mm to 50 mm: 30 mm (Santos-Concejero et al., 2015), 35 mm (Shannon et al., 2017), 40 mm or 41 mm (Bourdillon et al., 2014; Decroix et al., 2016, 2018; Fan et al., 2013, 2018; Ferguson et al., 2018; Nielsen et al., 1999; Robertson et al., 2016; Wingfield et al., 2018, 2019), 45 mm (Billaut et al., 2010; Pires et al., 2016) and 50 mm (Hamlin et al., 2010). Therefore, all distances selected were around or just above distances commonly adopted in neuroscience more broadly and sport science research specifically. However, two studies did not report a source-detector separation distance (Liao et al., 2019; Shaw et al., 2020).

Baseline

Participant instruction, duration and environmental conditions are all important considerations when obtaining baseline data for accurate comparison of changes in experimental conditions from rest values. As Herold et al. (2018) highlighted, no general consensus exists concerning baseline duration. However, a 10-30 second baseline is suggested as a balanced consideration to remove the prospect of random physiological fluctuations for shorter baselines and the prospect of mind-wandering for longer baselines. Pertinently, on this latter point, mind wandering has been implicated in the medial PFC as measured by fNIRS (Durantin et al., 2015). Furthermore, it would be prudent to consider changes in PFC activity as a function of exercise task demands that appear to reflect ‘on’ and ‘off’ task foci (Radel et al., 2017).

Baseline procedures in the reviewed studies included both 60-second (Robertson et al., 2016; Wingfield et al., 2018, 2019) and 120-second durations (Billaut et al., 2010; Decroix et al., 2016, 2018; Hamlin et al., 2010; Pires et al., 2016; Santos-Concejero et al., 2015). The remaining studies used longer or undetermined baseline durations that often served to provide baseline data for several study measures, including fNIRS (Bourdillon et al., 2014; Fan et al., 2013, 2018; Ferguson et al., 2018; Liao et al., 2019; Nielsen et al., 1999; Shannon et al., 2017; Shaw et al., 2020). Concerning the broader base of exercise research, a 30-second baseline was most commonly used, although several studies opted for longer durations (Herold et al., 2018). In addition, other techniques were also employed by reviewed studies to reduce movement artefacts and environmental stimuli as confounds during baseline recordings. These included removing auditory and visual distractions (Wingfield et al., 2018, 2019), asking participants to remain silent (Billaut et al., 2010; Decroix et al., 2016, 2018), to restrict bodily movement (Decroix et al., 2016, 2018; Pires et al., 2016) and to close their eyes (Billaut et al., 2010; Pires et al., 2016; Robertson et al., 2016; Santos-Concejero et al., 2015).

Given that posture-dependent differences in cerebral haemodynamics have been observed in the healthy adult brain (Tachtsidis et al., 2004), it is important to ensure that baseline procedures reflect the postural demands of the task. Therefore, for consistency across studies, most reviews recommend a seated position for baseline protocols (Herold et al., 2018). Promisingly, most reviewed studies used posture-appropriate baseline procedures that reflected the seated nature of the exercise task adopted (i.e., cycling). A noted exception is the use of a standing baseline in one study where the exercise task required treadmill running (Billaut et al., 2010). However, a seated baseline was conducted in two studies also using a running task (Santos-Concejero et al., 2015; Shaw et al., 2020).

Differential Pathlength Factor (DPF)

To derive quantitative concentration changes from measurements of light attenuation, the DPF must be known. Therefore, correct calculation of the DPF is vital to minimize the possibility of cross-talk (i.e., incorrect separation of chromospheres; Uludağ et al., 2004). Using constant DPF values is suboptimal given that subject-to-subject variability leads to systematic errors in fNIRS signal measurement (Strangman et al., 2002). Therefore, measurement of DPF values as a function of age is recommended (Duncan et al., 1996).

Six of the reviewed studies opted to use an age-dependent DPF (Billaut et al., 2010; Bourdillon et al., 2014; Decroix et al., 2016; Fan et al., 2013, 2018; Shannon et al., 2017), while eight studies opted to specify constant wavelength values (Ferguson et al., 2018; Hamlin et al., 2010; Nielsen et al., 1999; Pires et al., 2016; Robertson et al., 2016; Santos-Concejero et al., 2015; Wingfield et al., 2018, 2019). However, three studies did not report DPF values (Decroix et al., 2018; Liao et al., 2019; Shaw et al., 2020). The use of age-dependent DPF values appears to be rare in the broader field of exercise-based fNIRS work to date (Herold et al., 2018). Therefore, the reviewed studies did not fully follow this trend with a sizeable minority using an age-dependent formula.

Artefacts

There are two main sources of fNIRS signal noise: (i) physiological oscillations (e.g., due to heart rate beats) and (ii) movement-related artefacts (e.g., signal changes evoked by bodily movements; Pinti et al., 2019). Pertinently, these sources of noise are of particular importance to exercise-based research. Filtering methods are typically adopted to reduce the contribution of noise to task-evoked haemodynamic response, therefore improving the signal-to-noise ratio. In addition, several software packages are now available that allow for signal processing through algorithmic checks and visual assessment (for an overview, see Orihuela-Espina et al., 2010). Despite commonplace efforts to improve the signal-to-noise ratio in exercise-based research (Herold et al., 2018), only one study referred to taking these extra measures by using a low-bandpass filter (Pires et al., 2016).

Data Analysis

To account for individual variability, a baseline correction to fNIRS data should be performed prior to analysis. Studies often perform ANOVA's to inferentially analyse mean values, however, the use of median values may be preferable as they are less susceptible to outliers for datasets with small samples (Herold et al., 2018). This is particularly pertinent for sport science research where small sample sizes are commonplace (Bernards et al., 2017). Using both O_2Hb and HHb provides different strengths for analysis and interpretation. As Orihuela-Espina et al. (2010) summarize, O_2Hb is more sensitive to cerebral blood flow, but HHb may better reflect oxygen supply and demand. Many studies also commonly report the tissue oxygenation index (TOI), which is calculated as the proportion of O_2Hb relative to tHb concentration. Therefore, the TOI provides a relative balance between oxygen delivery and utilization (Tisdall et al., 2009).

Where appropriate, all studies performed a baseline correction of data to express concentration change from baseline. Mean values were used by 14 studies to perform an ANOVA or non-parametric equivalent (Billaut et al., 2010; Bourdillon et al., 2014; Decroix et al., 2016, 2018; Fan et al., 2013, 2018; Liao et al., 2019; Nielsen et al., 1999; Pires et al., 2016; Robertson et al., 2016; Santos-Concejero et al., 2015; Shannon et al., 2017; Wingfield et al., 2018, 2019). However, other analyses were performed, including mixed-effects models (Fan et al., 2018; Hamlin et al., 2010), correlations (Bourdillon et al., 2014; Wingfield et al., 2018, 2019) and linear regression analysis (Hamlin et al., 2010). This eclectic mix of inferential testing perhaps reflects the ongoing debate concerning the best practice for fNIRS data analysis. For instance, the inadequate removal of noise can lead to violations of assumptions for common statistical tests (Huppert, 2016). Only two studies did not report findings for at least O_2Hb and HHb (Decroix et al., 2018; Ferguson et al., 2018). However, these studies, alongside other reviewed work, did report findings for TOI (Decroix et al., 2018; Ferguson et al., 2018; Hamlin et al., 2010; Liao et al., 2019; Robertson et al., 2016; Santos-Concejero et al., 2015). Therefore, the data analysis techniques of reviewed studies broadly reflect the predominant use of

ANOVA’s to analyse at least O_2Hb in exercise-based research using fNIRS (Herold et al., 2018).

Other Considerations

Exercise task and protocol. A cycling-based exercise task was used by 13 studies (Bourdillon et al., 2014; Decroix et al., 2016, 2018; Fan et al., 2013, 2018; Ferguson et al., 2018; Hamlin et al., 2010; Liao et al., 2019; Pires et al., 2016; Robertson et al., 2016; Shaw et al., 2020; Wingfield et al., 2018, 2019). However, rowing (Nielsen et al., 1999) and running (Billaut et al., 2010; Santos-Concejero et al., 2015; Shannon et al., 2017) tasks were also used. The completion of a set-distance TT effort was required of participants in 13 studies (Billaut et al., 2010; Bourdillon et al., 2014; Fan et al., 2013, 2018; Ferguson et al., 2018; Hamlin et al., 2010; Liao et al., 2019; Pires et al., 2016; Santos-Concejero et al., 2015; Shannon et al., 2017; Shaw et al., 2020; Wingfield et al., 2018, 2019), while four studies demanded a set-time effort (i.e., 20-minute TT; Decroix et al., 2016, 2018; Nielsen et al., 1999; Robertson et al., 2016). Many studies use stationary cycling exercise for fNIRS-based research as it is comparatively easy to maintain a consistent posture despite high workloads (Perrey & Besson, 2018), although direct comparison across exercise modes is lacking. Nonetheless, direct comparison between supine and recumbent cycling revealed little difference in PFC oxygenation as measured by fNIRS (Faulkner et al., 2016).

Concerning protocol design, many of the recommendations are inappropriate to apply to the reviewed literature as they relate to neurocognitive domains (e.g., weighing the pros and cons of event-related vs. block designs; Chee et al., 2003). In exercise-based research, most studies have opted to use a central tendency value calculated over distinct time periods (i.e., windows or epochs; Herold et al., 2018). This approach was adopted across most reviewed studies, with only two studies preferring to simply analyse average values for the entirety of the exercise task (Nielsen et al., 1999; Shannon et al., 2017). This may be due to the comparatively short nature of the tasks used in these studies, namely a 6-minute rowing effort and a 3 km treadmill TT.

Region of interest (ROI). Ten studies opted to place fNIRS optodes over the dorsolateral PFC, corresponding to Fp1-F3 and Fp2-F4 regions according to the international EEG 10-20 system (Billaut et al., 2010; Bourdillon et al., 2014; Decroix et al., 2016, 2018; Liao et al., 2019; Pires et al., 2016; Robertson et al., 2016; Santos-Concejero et al., 2015; Wingfield et al., 2018, 2019). Three studies did not reference a particular brain ROI but did provide anatomical measurements for determining optode placement (Ferguson et al., 2018; Shannon et al., 2017; Shaw et al., 2020), while four further studies did not provide such measurements (Fan et al., 2013, 2018; Hamlin et al., 2010; Nielsen et al., 1999). It should be noted that research objectives may dictate the necessity to highlight a ROI. For the seven studies not using the 10-20 system, it appears that the assessment of Cox is the dependent variable, with no specific hypotheses concerning a ROI stated. However, Cox during exercise appears region-dependent. For instance, deception regarding the expected length of exercise related to changes in oxygenation between brain areas involved in the central executive network and default mode network (Radel et al., 2017). As outlined in Chapter 3, this highlights the need for research into the functions of the PFC in regulating pacing.

The dorsolateral PFC, a ROI in several of the reviewed studies, is implicated in the ability to represent and maintain the attentional demands of a given task in working memory (MacDonald et al., 2000) and regulation of affective state (Davidson, 2002). Therefore, the dorsolateral PFC has become a ROI for the psychology of endurance performance, given its plausible role in the ability to integrate external (e.g., competitor behaviour) and internal (e.g., perceived exertion) stimuli to inform pacing (Hyland-Monks et al., 2018), and to control stress responses to aid exercise tolerance (Bigliassi & Filho, 2022; Ekkekakis, 2009). Moreover, according to the RAH model previously outlined (Dietrich & Audiffren, 2011), during high-intensity exercise above the ventilatory threshold, lateral areas of the PFC are compromised to preserve more vital brain regions. This leads to a compromise of cognitive control and therefore top-down self-regulation of endurance performance. As a result, fNIRS-based research has investigated the use of self-regulatory interventions to mitigate such effects, including the use of imagery (Tempest & Parfitt, 2013).

Findings of Reviewed Studies

A summary of the reviewed studies is presented in Table 4.3, including key sample characteristics, methodology and findings. The reviewed studies provide insight into the cerebral haemodynamic response during self-paced exercise. This research will contribute to our understanding of how the PFC and executive function help self-regulate endurance performance. Indeed, the PFC is indirectly linked to motor control through the premotor area, which may allow the PFC to appraise signalling from afferent feedback to, for example, increase exercise tolerance (Robertson & Marino, 2016).

Firstly, Billaut et al. (2010) measured the PFC haemodynamics of trained runners during a full-effort 5 km treadmill run. O_2Hb and HHb both increased in the first 2.5 km before levelling off, with O_2Hb decreasing and HHb increasing in the final 500 m. According to the authors, these findings demonstrate that some degree of homeostatic disturbance (i.e., cerebral deoxygenation) is tolerated to achieve an end-spurt (i.e., a reservation of energy to enable a tactical increase in pace in the later stages of a race; St. Clair Gibson et al., 2013). In subsequent research, elite Kenyan runners completed the same 5 km protocol (Santos-Concejero et al., 2015). Contrasting with Billaut et al. (2010), O_2Hb remained stable beyond the halfway mark to the finish and HHb increased through to completion. This difference is possibly attributable to early lifestyle factors (e.g., being born at high altitude) leading to cerebrovascular remodelling, which may better enable the preservation of Cox during high-intensity aerobic exercise within highly-trained populations. It could also relate to the pacing strategies adopted by runners, as no end-spurt was observed and therefore larger homeostatic change and reduction in Cox. Interestingly, a review of cortical haemodynamics during incremental maximal testing found that oxygen values dropped markedly in untrained participants compared to aerobically-trained counterparts at very hard intensities ($\geq VO_{2peak}$; Rooks et al., 2010).

Table 4.3 Overview of Reviewed Studies.

Study	Sample & characteristics	Method & ROI	Selected findings
Billaut et al. (2010)	11 well-trained male distance runners (training volume: 11.1 ± 3.5 h week^{-1}).	5 km treadmill TT performance. Left PFC (Fp1-F3[a])	O_2Hb and HHb↑ in first 2.5 km; O_2Hb↓ and HHb↑ in last 500 m.
Bourdillon et al. (2014)	13 well-trained male cyclists (W_{max}: 385 ± 30 W).	Hypoxia sensitivity test followed by normoxia vs. hypoxia on 15 km cycling TT	Hypoxia-induced HHb↑ correlated with drop in PO.

		performance. Left PFC (Fp1[a])	
Decroix et al. (2016)	12 well-trained male cyclists (VO_{2max}: 63.0 ± 3.5 mL/kg·min−1).	Cocoa flavanol vs. PLA on 30 min cycling TT performance. Left PFC (Fp1-F3[a])	O_2Hb, HHb and tHb↑ across TT, but not between conditions.
Decroix et al. (2018)	14 well-trained male cyclists (VO_{2max}: 62.9 ± 5.8 mL/kg·min−1).	7-day cocoa flavanol intake vs. PLA in normoxia and hypoxia on 20 min cycling TT performance. Left PFC (Fp1-F3[a])	In hypoxia, large TOI↓ in first 5 min then stabilized, but no differences related to cocoa flavanol intake.
Fan et al. (2013)	10 well-trained male cyclists (VO_{2max}: 63.3 ± 6.6 mL/kg·min−1).	Normoxia vs. hypoxia with and without end-tidal Pco_2 clamping on 15 km cycling TT performance. 'Left prefrontal lobe'	No significant change in O_2Hb and HHb using Pco_2 clamping.
Fan et al. (2018)	12 well-trained male cyclists (W_{max}: 381 ± 36 W).	3-day nitrate intake vs. PLA in normoxia and hypoxia on 15 km cycling TT performance. 'Left prefrontal lobe'	O_2Hb and HHb↑ in nitrate vs. PLA in normoxia, but no effect in hypoxia.
Ferguson et al. (2018)	12 well-trained male cyclists (W_{max}: 396 ± 42 W).	Neutral (23°C) vs. cold (0°C) vs. cold + hyperoxia on 15 km cycling TT performance. 'Left forehead'	TOI↑ in neutral vs. cold; cold + hyperoxia unchanged from neutral after 2.5 km.
Hamlin et al. (2010)	9 (7 male) well-trained endurance athletes (VO_{2peak} placebo group: 65.9 ± 1.6, experimental group: 68.4 ± 5.3 mL/kg·min−1).	10 days of 90 min intermittent hypoxic exposure (IHE) vs. PLA on 20 km cycling TT performance. 'Left forehead'	TOI↓ during final stages of TT caused by IHE-induced hypocapnia. Both tHb and TOI correlated with change in performance.
Liao et al. (2019)	10 national-level male triathletes (VO_{2max}: 59.4 ± 1.4 mL/kg·min−1).	Normoxia PLA vs. hypoxia PLA vs. hypoxia + carbohydrate intake on 40 km cycling TT performance with sprint intervals. Right PFC (Fp2[a])	TOI and tHb↑ 0-10 km then stabilized across TT, but no amelioration of hypoxic effects with carbohydrate intake.
Nielsen et al. (1999)	11 elite male rowers (competed at world championship level).	Normoxia vs. hyperoxia on 'all-out' 6 min rowing effort. 'Forehead just below hairline'.	Greater working capacity (i.e., PO↑) in hyperoxia attributable to Cox maintenance.

Pires et al. (2016)	9 well-trained male cyclists (VO_{2max}: 57.5 ± 6.2 mL/kg·min−1).	Max graded cycling test (GXT) and 4 km cycling TT performance. Left PFC (Fp1[a])	O_2Hb↑ greater in GXT vs. TT through 20-60% completion, but higher at finish in TT.
Robertson et al. (2016)	11 well-trained male cyclists (VO_{2max}: 4.4 ± 0.61 L/min−1).	Exogenous cortisol vs. PLA on 30 min cycling TT performance with 5 sprint intervals. PFC (Fp1-F3 and Fp2-F4[a]).	Progressive TOI↓ during sprints. nTHI↓ greater in cortisol vs. PLA in sprints 4 and 5.
Santos-Concejero et al. (2015)	15 elite male Kenyan distance runners born at high altitude (VO_{2max}: 71.9 ± 5.1 mL/kg·min−1).	5 km treadmill TT performance. Left PFC (Fp1-F3[a])	O_2Hb↑ in first 2.5 km then stabilized: HHb↑ until completion.
Shannon et al. (2017)	10 healthy males (VO_{2max}: 60.9 ± 10.1 mL/kg·min−1).	Nitrate vs. PLA in moderate and severe hypoxia on 3 km treadmill TT performance simulating hike. 'Medial PFC'	Superior performance and O_2Hb, HHb and tHb↓ in nitrate vs. PLA.
Shaw et al. (2020)	12 (10 male) well-trained cyclists (VO_{2max}: 55 ± 6 mL/kg·min−1).	14-day dark chocolate intake vs. PLA on 10 km cycling TT performance in hypoxia. 'Right side…above the eyebrow'.	O_2Hb, HHb and tHb↑ across TT, but not between conditions.
Wingfield et al. (2018)	10 well-trained male cyclists (VO_{2peak}: 63.6 ± 5.7 mL/kg·min−1).	Performance feedback vs. no feedback on 30 km cycling TT performance. Right PFC (Fp2-F4[a])	HHb↑ in final 2 km in feedback condition. PFC activity correlated with PO in feedback condition.
Wingfield et al. (2019)	9 well-trained male cyclists (VO_{2peak}: 63.6 ± 5.7 mL/kg·min−1).	3 30 km cycling TT's with end-point deception used in two TT's (24 km and 36 km in distance). Right PFC (Fp2-F4[a]).	O_2Hb, RPE↑ and PO↓ in latter stages of 36 km TT when deception evident.

Note. Selected findings presented prioritize fNIRS and cerebral haemodynamics. ↓ = decrease, ↑ = increase, Cox = cerebral oxygenation, nTHI = normalized tissue haemoglobin index, PFC = prefrontal cortex, HHb = deoxyhemoglobin, O_2Hb = oxyhemoglobin, PLA = placebo, PO = power output, RPE = rating of perceived exertion, ROI = region of interest, tHb = O_2Hb + HHb, TOI = tissue oxygenation index, TT = time-trial.
[a] In reference to the international electroencephalographic (EEG) 10–20 system.

Beyond the more exploratory work above, research has also explored the cerebral haemodynamic response to endurance performance with experimental manipulations. For instance, Pires et al. (2016) examined the influence of two VO_{2max}-matched exercise modes on PFC oxygenation in trained cyclists. PFC O_2Hb

was higher between 20-60% completion during an incremental test compared to a 4 km TT, but O_2Hb was higher in the TT at 100% completion. Despite these PFC perturbations, activity in the primary motor cortex was maintained throughout the duration of both exercise bouts. This suggests that there is a preferential preservation of the primary motor cortex during strenuous exercise. Moreover, it supports the notion of PFC and motor cortex integration in exercise regulation. However, reviewed studies most commonly investigated changes in oxygen availability to bodily tissues to simulate altitude change. Nielsen et al. (1999) measured haemodynamic response over the forehead of elite rowers completing an all-out 6-minute rowing effort, with inspired oxygen fraction at .21 (i.e., normoxia) versus .30 (i.e., hyperoxia). A greater work capacity (i.e., increased power output) and Cox were observed in hyperoxia, despite no difference in muscle oxygenation across the conditions. The findings suggest that an elevated inspiratory oxygen fraction increased exercise performance related to maintained Cox, rather than to any effect on the working muscles. In addition, Bourdillon and colleagues found hypoxia-induced increases in HHb correlated with decreases in power output during a 15 km TT among trained cyclists (Bourdillon et al., 2014). Taken together, these findings suggest that brain oxygenation may play a limiting role in aerobic exercise capacity. If this notion is correct, there is potential for interventions aimed at improving Cox during exercise and ultimately as a result, exercise capacity.

Further research has investigated environmental effects and ergogenic aids on exercise performance in normoxia, hypoxia and hyperoxia. Hamlin et al. (2010) asked trained endurance athletes to complete 10 days of intermittent hypoxic exposure (IHE) training prior to performing a 20 km TT. During the final stages of the TT, IHE-induced elevations in muscle O_2Hb and reductions in cerebral TOI were observed, with no subsequent effect on performance. The reduction in oxygenation may relate to cerebral vasoconstriction through reduced CO_2 levels (i.e., hypocapnia) due to IHE. This is supported by moderate-to-strong relationships observed between TOI, tHb and performance. Therefore, the lack of improvement may relate to a ‘balancing out' of beneficial adaptations to muscle, but not brain. Fan et al. (2013) examined the effect of clamping partial pressure of end-tidal CO_2 on cerebral perfusion and performance during a 15 km TT by trained cyclists in severe hypoxia. Clamping normalized PFC oxygen delivery to normoxic values. However, clamping did not result in a performance improvement in hypoxia. Therefore, the authors refute the hypothesis that cerebral deoxygenation caused by hypoxia-induced hypocapnia reduces exercise performance. Following on, Ferguson et al. (2018) assessed the impact of hyperoxia in ameliorating the negative impact of hypothermia on 15 km TT performance in trained cyclists. Under conditions of hypothermia, hyperoxia restored performance levels to that seen at neutral temperatures. Although cerebral TOI was higher at neutral temperatures compared to cold conditions, TOI levels were similar between neutral and cold plus hyperoxic conditions after the 2.5 km point. The findings suggest that the restoration of performance via hyperoxia is related to oxygen availability.

Research has attempted to explore the possibility of ‘boosting’ Cox to aid cognition and endurance performance via cocoa flavonoids, which possess nitric oxide-induced vasodilatory properties (Socci et al., 2017). Decroix et al. (2016) tested the impact of cocoa flavanols on 30-minute TT performance in trained cyclists. Although PFC oxygenation increased at baseline in the experimental group, this was not reflected in superior Stroop task performance pre-exercise. Cocoa flavanol intake did not significantly influence the exercise-induced haemodynamic response, which likely overruled any smaller detectable impact of cocoa flavanols on Cox during exercise that was observed at rest. Extending this research, Decroix et al. (2018) investigated 7-day cocoa flavanol intake on 20-minute TT performance in both normoxia and hypoxia among trained cyclists. Although cocoa flavanol intake raised PFC oxygenation levels at rest, no differences were observed in TT performance or oxygenation levels during exercise. Most recently, Shaw et al. (2020) used trained cyclists to assess the impact of 14-day dark chocolate (high in flavonoids) intake on 10 km TT performance at simulated altitude. Although some metabolic benefits to dark chocolate intake were observed, no benefits to PFC oxygenation or performance were found.

Dietary nitrate has been shown to restore metabolic function and muscular endurance performance to normoxic levels at simulated altitude (Vanhatalo et al., 2011), but the effects on Cox during whole-body, endurance performance remain unclear. Fan et al. (2018) tasked trained cyclists with completing a 15 km TT in normoxic and hypoxic conditions after three days of dietary nitrate intake. Dietary nitrate selectively improved PFC oxygenation during exercise in normoxia, but these effects were not extended to hypoxia. This lack of change in hypoxia may relate to compensatory mechanisms to protect the oxygen supply to vital homeostatic control centres. A further study investigated nitrate-rich beetroot supplementation on 3 km treadmill TT (set at 10% gradient) performance in both moderate and severe hypoxia (Shannon et al., 2017). PFC O_2Hb, HHb and tHb were lower in the beetroot condition, which may reflect differential PFC perfusion related to superior performance via beetroot intake. This may also indicate a lower cerebral blood volume or oxygen extraction rate. Cerebral deoxygenation is hypothesized to compromise executive function and play a limiting factor in exercise tolerance (Subudhi et al., 2009).

Aside from flavonoid- and nitrate-rich interventions, others have tested the impact of carbohydrate and exogenous cortisol on exercise performance and PFC haemodynamics. In one study, carbohydrate intake failed to ameliorate hypoxia-induced deleterious effects on 40 km TT performance and PFC haemodynamics (Liao et al., 2019). Following on, as exogenous cortisol has been shown to increase risk-taking behaviour (Putman et al., 2010), Robertson et al. (2016) wanted to explore the impact of exogenous cortisol on trained cyclists' performance in a 30-minute TT featuring five 30-second sprint intervals. A greater reduction in normalized tissue haemoglobin index (nTHI; O_2Hb + HHb expressed as change from baseline in a.u.) was observed in the latter sprint intervals in the cortisol condition, indicating greater PFC desaturation and blood volume. However, no differences in TT performance were found across conditions.

The nascency of the intervention-based research presented above offers an opportunity to learn from and build on this work moving forward. Firstly, it is suggested that testing at a more ecologically valid genuine high altitude or in hypobaric hypoxia may elicit different physiological responses than normobaric hypoxia (Shannon et al., 2017; Shaw et al., 2020). However, both normobaric hypoxia and hypobaric hypoxia have been observed to induce broadly similar responses to terrestrial altitude, and therefore may be considered acceptable surrogates (Woods et al., 2017). Following on, it is also important to consider gender differences in response to interventions. For instance, Fan et al. (2018) refer to unpublished data showing an enhanced cerebrovascular response to nitrate intake in male, but not female participants. Likewise, one should consider fitness status. A meta-analysis found a small ergogenic effect of nitrate intake on exercise performance in non-athletes, but this was not extended to athlete populations (Campos et al., 2018). Lastly, although the scope of this review is limited to the PFC, it is feasible that interventions elicit more global changes in the brain during exercise. For instance, flavonoids have been observed to increase cerebral blood flow in several areas of the brain, including the anterior cingulate cortex (Lamport et al., 2015). Interestingly, functional adaptations to the anterior cingulate cortex through aerobic training are theorized to be a possible mechanism for enhanced resistance to mental fatigue effects on exercise performance (Martin et al., 2016).

There is a rich history of work that highlights how feedback deception or removal can influence subjective experience (e.g., perceived exertion), exercise economy and endurance performance (Jones et al., 2013). Wingfield et al. (2018) examined the influence of performance and distance feedback blinding on 30 km TT performance by trained cyclists. When feedback was provided, power output was higher in the final 2 km of the TT and was strongly correlated with HHb. These findings suggest some neural influence of the PFC over pacing by top-down regulation of physiological reserve in anticipation of an end-spurt. Complementing this research, Wingfield et al. (2019) investigated the performance of trained cyclists across three ‘30 km’ TT’s. However, feedback was withheld from participants and two trials were 24 km and 36 km in length. Rating of perceived exertion was significantly higher in the latter half of the 36 km versus 24 km TT. Although not significant, O_2Hb was higher at 70% completion in the 36 km versus 24 km TT. The results point to the PFC increasing perceived exertion to reduce the risk of catastrophic failure by driving down perceived exertion once end-point deception was detected. Therefore, while performers may have a pre-planned pacing strategy in mind, subconscious processes may also help govern physiological resources to avoid premature fatigue (Micklewright, Kegerreis et al., 2017). This work inspired the research conducted in Chapter 5 that investigates the sequential removal of course knowledge and performance feedback on TT performance, cerebral haemodynamics, and perceptual experience.

Conclusion

Promisingly, the small but growing body of literature reviewed here largely adopted some, but not all of the best practice guidelines for fNIRS use more widely and for exercise-based research specifically. However, there were several important guidelines that not all studies adopted, or at least had omitted from reporting in their method sections. As advances in sport performance are predicated on ‘marginal gains’, methodological rigor when using fNIRS technology is important to ensure sensitivity to detect meaningful changes in cortical activity. Following on, the body of literature presented here suggests that some degree of homeostatic disturbance (i.e., cerebral deoxygenation) is tolerated under high workload, but cerebral oxygen availability is a limiting factor on aerobic exercise performance. Furthermore, the PFC would appear to play a key role in integrating performance feedback to govern the self-regulation of endurance performance, and this is subject to further investigation in Chapter 5. Although no benefits were observed for flavonoids, nitrate-rich interventions showed some benefits to exercise performance and PFC perfusion. However, future work that addresses the limitations of the research presented here may provide a more conclusive picture. Finally, studies reviewed predominantly used trained and elite-level male athletes, with only four participants having been female. Therefore, more research is needed to ascertain the effects of both fitness status and sex on cerebral perfusion during self-paced exercise.

Chapter 5 The Influence of Task Knowledge and Feedback on Cycling Performance: Insights from Prefrontal Cortex Haemodynamic Measurement and Executive Function Testing.

Abstract

In recent years, both propositional and experimental research has explored the self-regulation of endurance performance. The internal and external sources of information used to self-regulate performance, and the cognitive processes that underlie these efforts are of particular interest. For the first time, this study sought to examine the use of performance feedback and course knowledge on cycling time-trial performance over a race-like simulation with undulating terrain, using cognitive testing and functional near-infrared spectroscopy (fNIRS). This helped to provide insight into the psychological mechanisms that may contribute to pacing behaviour. Descriptive findings are reported and discussed in a case study format, with the hope that this ‘proof of concept’ can be expanded in future research.

Introduction

Observers and participants alike can appreciate the vast and challenging terrain that grand tour cycling presents. In the 2022 Tour de France, the riders covered 3,328 km across 3 weeks (with two rest days), having climbed mountain passes over 1500 m high in the unforgiving Pyrenean and Alpine ranges (Dabbs & Thewlis, 2022). Such feats are not reserved for the elite athletes, with the amateur equivalent, L'Etape, requiring keen cyclists to cover 167 km and 4700 m of positive altitude change across three climbs in one day in the 2022 edition of the race (L'Etape du Tour de France, n.d.). Therefore, for athletes to complete such a challenge, effective distribution of workload and energy expenditure across the demands of the task (i.e., pacing) is crucial (Abbiss & Laursen, 2008). Notably, current theories are preceding to converge on the idea of conscious or subconscious governance of endurance performance. The integrative governor model (St. Clair Gibson et al., 2018) proposes that a 'governor' (not a specified brain area *per se*), through the weighting of competing psychological and physiological drives, subconsciously modulates motor unit recruitment to ensure that endurance performers can effectively pace workload while avoiding catastrophic failure of homeostasis. For this governor to operate efficiently, duration and end-point knowledge of exercise (e.g., distance to the race finish line) is central.

As highlighted in Chapters 1 and 3, research has provided a cognitive perspective on the importance of self-regulation to endurance performance. Briefly, Brick, MacIntyre, and Campbell (2016) proposed the cognitive control of exercise through both proactive (i.e., goal-directed) and reactive (i.e., automatic) control mechanisms. Empirical support for this notion is provided by research showing that only reactive control mechanisms are engaged during externally controlled exercise, as evidenced in the measurement of thought processes (Brick, Campbell et al., 2016) and brain activity patterns (Chacko et al., 2020). In turn, proactive mechanisms (e.g., self-regulatory control efforts) were engaged when faced with an unexpected change in task difficulty, requiring an alteration in pacing strategy (Brick et al., 2019). Moreover, research has pointed to an athlete's self-regulatory skills, underpinned by top-down executive functions that are associated with goal-directed behaviour (e.g., selective attention, inhibition and working memory), explaining differences in their endurance performance. Indeed, superior ultra-marathon runners (determined by finish time) displayed better inhibitory control, not only over motor responses but also over interfering and distracting information (Cona et al., 2015). Moreover, more experienced cyclists were better able to mitigate the effects of mental fatigue (induced by executive function testing) on subsequent cycling time-trial (TT) performance (Martin et al., 2016). This is perhaps also manifest in the greater use of self-regulatory efforts by more experienced cyclists versus their untrained counterparts during TT performance (Massey et al., 2020; Whitehead et al., 2018). This was in part corroborated by the greater use of power output (PO) feedback to self-regulate effort by trained persons observed in Chapter 2.

As highlighted above, integrating external and internal information to gauge effort and pace endurance activities is crucial to performance. The monitoring of PO and heart rate in professional bike racing to estimate exertion levels is testament to this (Hettinga et al., 2012). Likewise, the importance of reconnaissance missions to breed familiarity with course profiles before races. Previous research has observed both deleterious (Micklewright et al., 2010) and null effects (Borg et al., 2020; Smits et al., 2016) of feedback blinding on cycling performance. However, as detailed in the discussion, methodological differences may account for the unequivocal findings. Further research has sought to explore the impact of feedback blinding at the level of the brain. This has typically been achieved through measuring cerebral haemodynamics via functional near-infrared spectroscopy (fNIRS) as outlined in the method section. As detailed in Chapter 4, blinding to performance feedback (i.e., PO, heart rate and end-point knowledge) was observed to hinder cycling TT performance for the same perceived exertion (Wingfield et al., 2018). Interestingly, when such information was presented, PO was strongly associated with neural activity in the prefrontal cortex (PFC), implicated in executive control of exercise (Robertson & Marino, 2016). Moreover, experimental work has demonstrated how deception concerning exercise duration resulted in dynamic shifts in central executive (i.e., attentional control) and default mode networks (i.e., mind-wandering states) of the brain (Radel et al., 2017). In short, the central executive network was more active when participants believed the duration of exercise would be shorter (i.e., 10 minutes), with the default mode network more active when participants believed the duration of exercise would be longer (i.e., 60 minutes). In reality, exercise was terminated after 10 minutes in both instances. This research aligns with the notion of self-regulatory mechanisms (Brick, MacIntyre, & Campbell, 2016) being differentially engaged dependent on task demands (Brick, Campbell, et al., 2016; Brick et al., 2019; Chacko et al., 2020).

However, despite the undulating terrain featured in endurance events such as the Tour de France, research has yet to investigate the impact of course profile information and performance feedback on endurance performance and pacing, alongside PFC activity and executive function. One would suspect greater difficulty in gauging effort over undulating terrain compared to a flat course profile, which may require a greater engagement of executive functions to regulate goal-directed effort (e.g., maintaining a set intensity on more challenging uphill sections). In addition, task difficulty would likely increase if course profile or performance feedback were not available. Therefore, an investigation is warranted to shed light on the importance of performance feedback and knowledge of task demands (e.g., terrain) on the self-regulatory processes governing endurance performance in more ecologically valid settings. This study aims to achieve this through the assessment of cycling TT performance, psychophysiology, PFC activity via fNIRS, and prefrontal-dependent cognitive testing.

Method

Participant

A male triathlete who was familiar with pacing and self-regulating effort to performance feedback (e.g., PO and speed) and course profile information (e.g., elevation gain) was recruited to take part in the case study. The participant met De Pauw et al.'s (2013) criteria for ‘level 3’ indicators of ‘cycling status’: 1) Train at least 3 times a week, for a total of at least 5 hours, and cover at least 60 km; and 2) Has competitive experience in cycling. Demographic and physical activity characteristics are presented in Table 5.1. Following the Edge Hill University laboratory health and safety guidance, the participant was subjected to health screening and provided written informed consent. The participant was debriefed following their last visit and provided with the opportunity to ask any questions. Ethical approval was granted by the university research ethics committee.

Table 5.1 Participant Characteristics.

Characteristics	
Age (years)	39
Body weight (kg)	72.1
Height (cm)	172.0
Body Mass Index (kg/m^2)	24.0
Body fat percentage (%)	16.4
Weekly physical activity (hours)	6.0

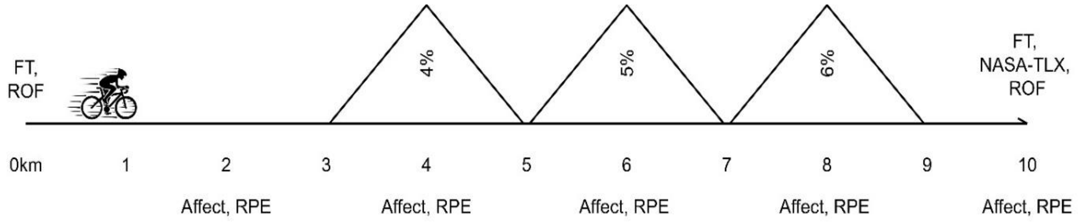
Design

A case study design was adopted due to difficulties in completing a full-scale experiment (see Author Notes and Chapter 1). While inferential analysis is not possible with case study designs, they can be useful to adopt when embarking on new research areas to provide a proof of concept for future work to build on (Barker et al., 2013). In the context of this study, fNIRS is a relatively new technology within sport and exercise psychology, and as highlighted in Chapter 4, best-practice standards have not always been followed. Therefore, as an initial phase in addressing the research aims, there is utility in conducting a case study.

Materials and Measures

Cycling time-trial. To measure TT performance, the Racermate software and electromagnetically-braked Velotron cycle ergometer (Racermate: Seattle, USA) was used to simulate a laboratory-based cycling TT. The software and bike allowed for the completion of a simulated TT course, including an avatar representing participant distance covered (km), speed (km.hr^{-1}), PO in watts (W), and cadence (r.min^{-1}). The course completed by the participant was 10 km in distance, with 3 hill ascents of 1 km starting at 3 km, 5 km, and 7 km, with gradients of 4%, 5%, and 6%, respectively. Each ascent was immediately followed by a descent of equal length and gradient. The course was otherwise completely flat (between 0-3 km and 9-10 km). See Figure 5.1 for a diagram of the course profile. Racermate software achieves the simulation of undulating terrain through changes in the resistance of the Velotron cycle ergometer fly-wheel. The Velotron ergometer was positioned centrally 1.5 m apart from a 100 cm (height) x 180 cm (width) screen projection of the virtual environment. The Racermate software and Velotron ergometer have been used to effectively simulate TT’s in previous research (Whitehead et al., 2018) and demonstrate sound test re-test reliability (Sparks et al., 2016). To monitor heart rate, the participant wore a Garmin Forerunner 15 watch and heart rate strap (Garmin: Kansas, USA).

Figure 5.1 Time-Trial Course Profile.



Note. Percentages relate to the gradient of simulated hills. FT = flanker task, NASA-TLX = The NASA Task Load Index, ROF = Rating of Fatigue, RPE = Rating of Perceived Exertion.

fNIRS. Measurement of haemodynamics in the PFC was performed via fNIRS (Oxymon mk III, Artinis: Zetten, Netherlands). fNIRS methodology followed the guidelines presented in Chapter 4. Optode pairs (source-detector separation: 2.5 cm) were placed over the left and right prefrontal lobe at F3, F4, F5 and F6 (according to the international 10–20 electroencephalogram system; Table 5.2), corresponding to the left and right inferior and superior dorsolateral PFC (Figure 5.2). A dark elastic headband was placed over the optodes to secure them in place and block extraneous light. The differential path-length factor was adjusted according to the subject’s age (Duncan et al., 1996). The modified Beer-Lambert law was applied by the equipment software to calculate relative change in the concentrations of oxygenated haemoglobin (O_2Hb), deoxygenated haemoglobin (HHb) and total haemoglobin (tHb; O_2hb + HHb) concentrations measured in µmol of haemoglobin. To calculate baseline measures, the participant remained seated on the cycle ergometer without speaking or moving and with eyes open for 1 minute before completing exercise. Measurements were normalized to reflect the magnitude of change from baseline. The data was collected with a sampling frequency of 10 Hz.

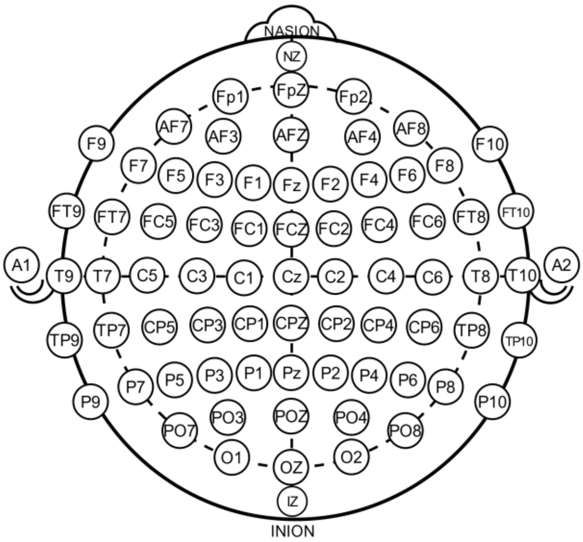
Table 5.2 Optode Placements for fNIRS Measurement.

Region of interest	10-20 system	Brodmann Area
Left inferior dlPFC	F5	46
Left superior dlPFC	F3	8

Right inferior dlPFC	F6	46
Right superior dlPFC	F4	8

Note. 10-20 system = International 10–20 electroencephalogram system; dlPFC = dorsolateral PFC

Figure 5.2 International 10-20 System.

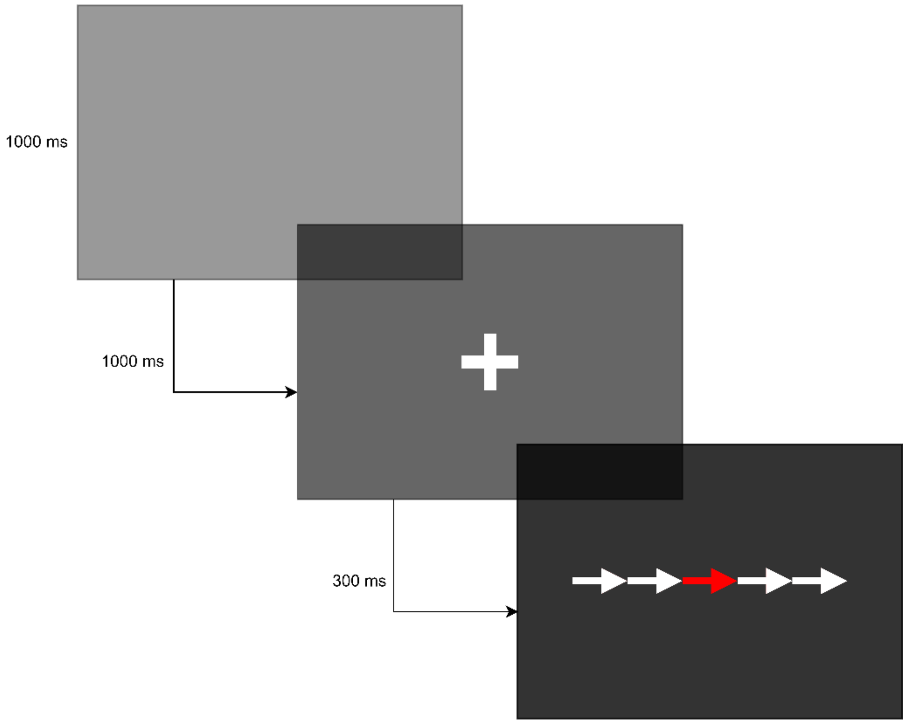


Note. This Photo by Brylie Christopher Oxley is licensed under CC0 1.0.

Several studies assessing exercise effects on PFC activity have focused on the dorsolateral PFC (e.g., Radel et al., 2017; Sudo et al., 2017; Tempest et al., 2017; Tempest & Parfitt, 2013, 2016). As detailed in Chapter 3, the dorsolateral PFC is of interest here and in this field of research due to its purported involvement in the central executive network and therefore attentional control (Radel et al., 2017). Moreover, the right dorsolateral PFC has been associated with exercise tolerance through affective control of stress response to exercise (Bigliassi & Filho, 2022). In addition, according to the dual-model theory, lateral areas of the PFC are compromised during exercise to preserve other brain regions when exercising above the ventilatory threshold, whereby interoceptive cues dominate, compromising cognitive control and therefore top-down self-regulation of endurance performance (Tempest et al., 2014).

Flanker task. To measure executive function and response inhibition, an Eriksen Flanker Task was devised in E-Prime (Psychology Software Tools: Sharpsburg, USA). The flanker task is detailed in Chapter 2. However, the version used in the present experiment was modified to include ‘switch’ trials. In the standard flanker task, participants are instructed to indicate which direction the centre arrow is facing as quickly and accurately as possible. However, in switch trials, when the centre arrow is presented in red ink, participants are instructed to ‘switch’ their response (i.e., pressing ‘D’, originally indicating left in the standard flanker task, when the centre arrow is facing right, e.g., → →→→→). Switch rule changes have been shown to have deleterious effects on task performance (Umebayashi & Okita, 2010), presumably through interference resulting from a residual carryover effect of stimulus-response retrieval for prior task rules in the working memory (Rubinstein et al., 2001). The test featured 120 trials in total, with 50% of trials featuring ‘standard’ congruent and incongruent stimuli, 40% featuring ‘switch’ congruent and incongruent stimuli, and 10% featuring neutral trials. Before stimuli are presented, a blank screen is shown for 1000 ms, followed by a priming fixation point for a further 1000 ms. Stimuli are then presented for 300 ms regardless of response time. Twenty practice trials are completed before the test commences. Response accuracy (%) and reaction time (RT) for correct responses (ms) are the key measures. The test is typically completed in ~5 minutes. A trial sequence for a switch congruent trial is presented in Figure 5.3.

Figure 5.3 A Flanker Task Trial Sequence for a Congruent Switch Trial.



Self-report measures. To measure fatigue, the Rating of Fatigue Scale (Micklewright, St. Clair Gibson et al., 2017) was completed by the participant pre- and post-task. To measure in-task rating of perceived exertion (RPE) and affective state, the 15-point Borg Scale (Borg, 1982) and the Feelings Scale (Hardy & Rejeski, 1989) were completed by the participant. To measure perceived physical and mental demand of participation, the NASA Task Load Index (Hart & Staveland, 1988) was completed by the participant post-task. Please see the references provided for validation of the above scales.

Protocol

For each visit, the participant was instructed to wear light athletic clothing and abstain from alcohol and vigorous exercise 24 hours prior to participation. In the initial visit, all pre-task measures were completed by the participant. The TT’s were completed in the same location at the same time of day (± 1 hour). Ahead of a baseline TT (TTBL), the participant was provided with a detailed course profile (Figure 1) and performance feedback (i.e., distance covered, speed, watts, cadence, and gearing) via a screen projection during the TT. The participant was instructed to complete the TT as fast as they possibly could. A 5-minute warm-up and cool-down at 50% of the participant’s heart rate reserve were completed before and after each TT to prevent injury and aid recovery. The participant completed the flanker task immediately before and after the TT. Self-report measures were taken from the participant as presented in Figure 1. Therefore, perceived exertion and affect were recorded at 2 km intervals and perceived fatigue was recorded before and after TT completion. The NASA Task Load Index was completed after each trial.

The participant then completed the same TT on three further occasions, between two days and a week apart. In the second TT (TTFull), the participant completed the TT under the same conditions as their initial visit, but this time fNIRS measurement was included. The third TT (TTNoPro) was completed under the same conditions as TTFull, except that the participant could not view the course profile beforehand and was not provided with distance feedback during the TT (and therefore lacked end-point knowledge). The fourth TT (TTNoFB) was completed under the same conditions as TTNoPro, but with the additional removal of PO and speed feedback during the TT.

Data Analysis

Mean PO and overall completion time are presented as an indication of performance across the trials. Relative PO ($_{r}$PO) was calculated for the final 250 m and periods of hill climbing (ascension phase only) and compared across the trials. Relative PO was calculated for the intervals mentioned as follows, $X\ _{r}PO = (X\ _{m}PO - TT\ _{m}PO)/TT\ _{m}PO)$, where ‘X’ is an interval of interest.

In line with data analysis recommendations detailed in Chapter 4, baseline corrected mean values for O_2Hb, HHb and tHb were calculated for each region of interest, for each 2 km interval and compared across each TT. Moreover, as mentioned in Chapter 3, PFC asymmetry is another line of enquiry to consider. The laterality index (LI) is considered one way to assess such asymmetries by comparing brain activation patterns across hemispheres and can be calculated as follows, $LI = (R-L)/(R+L)$, where ‘L’ and ‘R’ refer to a ROI in the left and right corresponding hemispheres (Borrell et al., 2022). Values range from -1 to 1, with a positive value (0 to 1) indicating right lateralization, and a negative value (-1 to 0) indicating left lateralization. Bilaterality is assumed for values between +0.2 and -0.2. To remove divisional error as a result of positive and negative values, negative values will be changed to zero with appropriate limitations considered (Borrell et al., 2022). Therefore, to assess lateralisation of the dorsolateral PFC during TT performance, the LI for O_2Hb for each ROI will be calculated for all intervals across all trials.

Mean flanker task response accuracy (%) and RT for correct responses (ms) were calculated for each trial, pre- and post-exercise, for normal and switch trials, and for each stimulus presented. Mean scores on self-report measurements were compared at the intervals stipulated in the protocol across each TT. For the NASA Task Load Index, mean scores for respective items were compared across TT’s.

Results

Given that the data presented is derived from a single case study, it is the interpretation of the researcher that any analysis on these grounds would be erroneous by way of conjecture. Therefore, the results presented are primarily for descriptive and exploratory purposes.

Time-Trial Performance and Self-Report Measures

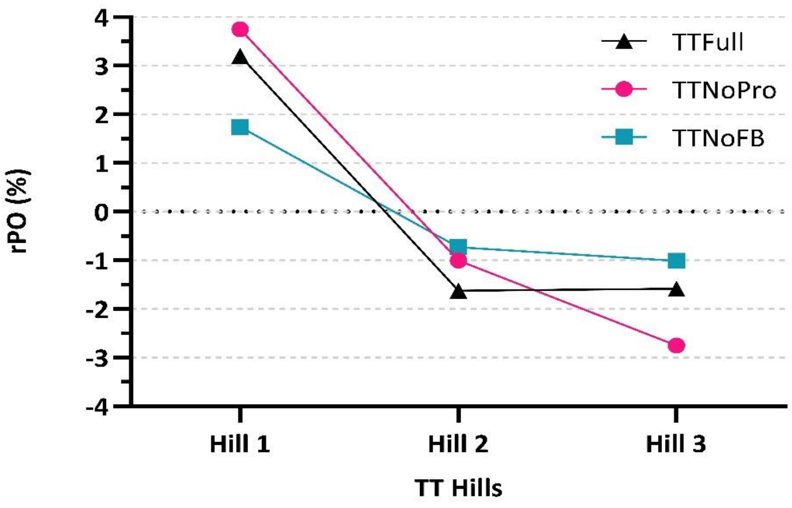
Overall indices of TT performance and pacing are presented in Table 5.3. It is evident that performance, as indicated by TT completion time and PO, was superior in TTFull relative to TTNoPro and TTNoFB, and in TTNoPro compared to TTNoFB. Moreover, end-spurt performance, as measured in rPO, was more pronounced in TTFull compared to TTNoPro and TTNoFB. rPO during the ascension phases of the TT hills is presented in Figure 5.4. rPO was highest across all TT's when climbing the first hill. However, pacing was most conservative in TTNoFB, with less deviation from mean PO compared to TTFull and TTNoPro when climbing all 3 hills.

Table 5.3 Mean Time-Trial Performance Data.

Time-trial	**Finish time (secs)**	**PO (W)**	**Final 250 m PO (W)**	**Final 250 m rPO (% change)[a]**
TTFull	1259.61	205.69	284.18	38.16
TTNoPro	1287.09	194.03	204.31	5.30
TTNoFB	1303.43	192.13	213.00	10.86

Note. PO = power output, rPO = relative power output, TTFull = full feedback, TTNoFB = no feedback, TTNoPro = no course or distance feedback.
[a]Calculated as relative change from mean TT PO.

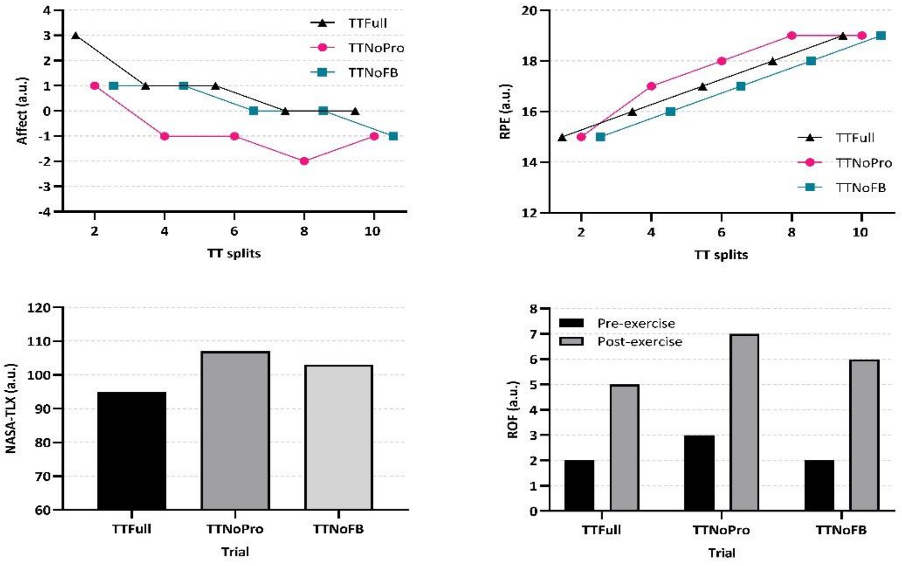
Figure 5.4 Mean Relative Power Output for Hill Climbs by Time-Trial.



Note. Calculated as change in % from Mean TT PO. rPO = relative power output, TTFull = full feedback, TTNoFB = no feedback, TTNoPro = no course or distance feedback.

Perceptual measures are presented in Figure 5.5. As expected, affective state and RPE followed a broadly inverse trend. As RPE increased across the TT's, affective state became progressively more negative. NASA Task Load Index composite scores were higher for the experimental trials relative to full feedback conditions. As expected, Rating of Fatigue scores were considerably higher post-TT compared to pre-TT.

Figure 5.5 Mean Perceptual Measures by Time-Trial.

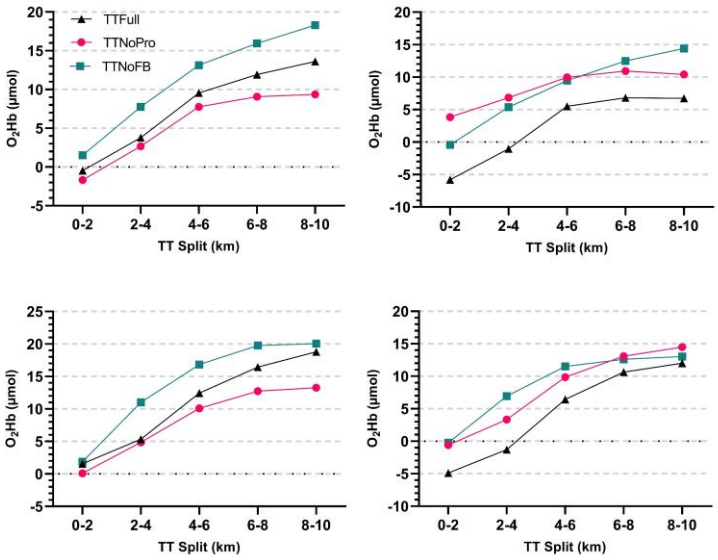


Note. Top left = affect, top right = Rating of Perceived Exertion, bottom left = The NASA Task Load Index, bottom right = Rating of Fatigue, TTFull = full feedback, TTNoFB = no feedback, TTNoPro = no course or distance feedback.

Prefrontal Haemodynamics and Executive Function

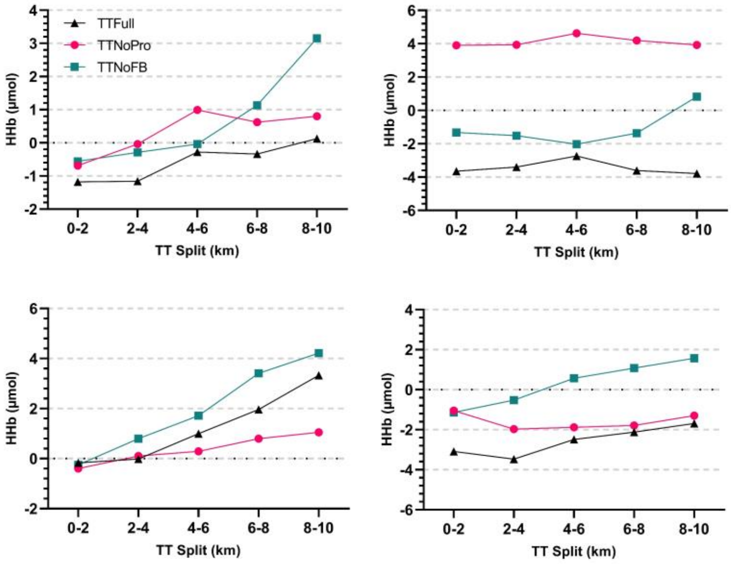
Baseline normalised O_2Hb, HHb and tHb values by region of interest and TT are presented in Figures 5.6, 5.7 and 5.8. Some trends are observable across the TT's and regions of interest. The most notable increase in O_2Hb occurs from 2-6 km, which coincides with the first hill climb. From 6 km to the finish, there is a plateau of O_2Hb. A broadly similar trend is seen for regional blood volume (tHb). O_2Hb, HHb and tHb values were observably greater in TTNoFB versus TTFull in all four regions of interest. tHb values in TTNoFB versus TTNoPro were higher in 3 out of 4 regions of interest, however the picture was more inconsistent and less conclusive for both O_2Hb and HHb. Laterality index calculations are presented in Table 5.4, with bilateral dominance evident for the majority of TT splits across all three trials.

Figure 5.7 Mean O_2Hb Values by Region of Interest and Time-Trial.



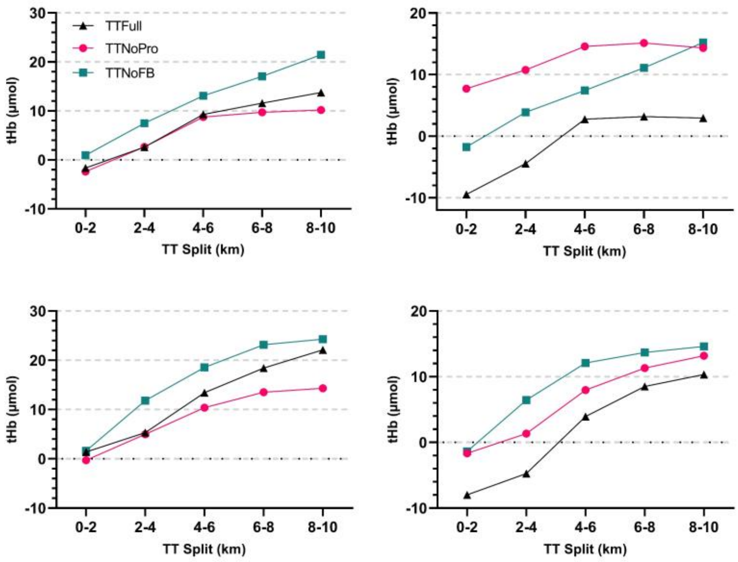
Note. Top left = right superior dorsolateral PFC (dlPFC), top right = right inferior dlPFC, bottom left = left superior dlPFC, bottom right = left inferior dlPFC. O_2Hb = oxyhaemoglobin, TTFull = full feedback, TTNoFB = no feedback, TTNoPro = no course or distance feedback.

Figure 5.6 Mean HHb Values by Region of Interest and Time-Trial.



Note. Top left = right superior dorsolateral PFC (dlPFC), top right = right inferior dlPFC, bottom left = left superior dlPFC, bottom right = left inferior dlPFC. HHb = deoxyhaemoglobin, TTFull = full feedback, TTNoFB = no feedback, TTNoPro = no course or distance feedback.

Figure 5.8 Mean tHb Values by Region of Interest and Time-Trial.



Note. Top left = right superior dorsolateral PFC (dlPFC), top right = right inferior dlPFC, bottom left = left superior dlPFC, bottom right = left inferior dlPFC. tHb = HbO_2 + HHb, TTFull = full feedback, TTNoFB = no feedback, TTNoPro = no course or distance feedback.

Table 5.4 Mean O_2Hb Values and Hemispheric Dominance Across Each Time-Trial.

Time-trial	**Split**	**Superior dlPFC**			**Inferior dlPFC**		
		Right	Left	LI	Right	Left	LI
TTFull	0-2 km	-0.47	1.56	L	-5.80	-4.89	B
	2-4 km	3.79	5.34	B	-1.03	-1.28	B
	4-6 km	9.56	12.43	B	5.50	6.44	B
	6-8 km	11.93	16.44	B	6.81	10.64	L
	8-10 km	13.62	18.78	B	6.74	12.02	L
TTNoPro	0-2 km	-1.68	0.10	L	3.83	-0.60	R
	2-4 km	2.68	4.87	L	6.83	3.33	R
	4-6 km	7.75	10.09	B	9.96	9.85	B
	6-8 km	9.08	12.73	B	10.93	13.09	B
	8-10 km	9.37	13.27	B	10.42	14.48	B
TTNoFB	0-2 km	1.52	1.87	B	-0.44	-0.23	B
	2-4 km	7.77	11.01	B	5.38	6.94	B

4-6 km	13.13	16.84	B	9.46	11.52	B
6-8 km	15.94	19.76	B	12.48	12.61	B
8-10 km	18.31	20.05	B	14.41	13.03	B

Note. Negative values were changed to zero to calculate the laterality index. Hemispheric dominance was calculated as follows: between +0.2 and -0.2 indicates bilateral dominance, +1 indicates complete left-sided dominance, and -1 indicates complete right-sided dominance. dlPFC = dorsolateral PFC, LI = laterality index, TTFull = full feedback, TTNoFB = no feedback, TTNoPro = no course or distance feedback.

The difference in flanker task RT for correct responses and accuracy from pre- to post-exercise by TT and stimuli is presented in Table 5.4. The most consistent observable trend relates to an improvement in RT post-exercise. However, there is no discernible difference in this trend across stimuli or TT's for both RT and accuracy.

Table 5.5 Change in Flanker Task Accuracy and Reaction Time Pre-Post Exercise.

Measure	**Time-trial**	**Normal trials**			**Switch trials**		
		Cong	Incong	Neutral	Cong	Incong	Neutral
Acc (%)	TTFull	-13.00	-13.00	10.00	-5.00	-10.00	NC
	TTNoPro	-4.00	-3.00	10.00	5.00	5.00	NC
	TTNoFB	-3.00	NC	NC	-5.00	NC	NC
RT (ms)	TTFull	-36.41	-17.24	21.81	-29.73	39.62	-30.45
	TTNoPro	-57.77	-53.72	-4.04	-102.39	-71.86	-129.80
	TTNoFB	-36.95	-32.50	-55.80	-58.68	-78.20	3.00

Note. Data is presented as change pre- to post-exercise. Acc = accuracy, Cong = congruent, Incong = incongruent, NC = no change, RT = reaction time, TT = time-trial, TTFull = full feedback, TTNoFB = no feedback, TTNoPro = no course or distance feedback.

Discussion

Time-Trial Performance and Self-Report Measures

This study aimed to assess the impact of course knowledge and feedback provision on cycling TT performance, PFC haemodynamics and cognition. Firstly, concerning performance, the TT was completed in a slower time when distance feedback and course knowledge was not presented (TTNoPro). Indeed, end-point knowledge appears to be central to the distribution of effort during self-paced endurance performance (St. Clair Gibson et al., 2018). Interestingly, as demonstrated in Chapter 2 and corroborated by similar work (Whitehead et al., 2017), thoughts concerning the remaining or covered distance increases as the endpoint nears, suggesting that this feedback becomes increasingly salient as an aid to pacing as the finish line approaches.

In addition, performance worsened further with the additional removal of PO and speed feedback (TTNoFB). In respect to pacing, a key factor in performance across the TT's relates to how effectively one can distribute their effort when tackling the hills featured. Interestingly, pacing was most conservative in TTNoFB when PO feedback was not available. This is best characterized by a significantly lower rPO on hill 1 in TTNoFB compared to TTFull and TTNoPro. Concerning the feedback provided, PO is the most comparable and useful measure of workload intensity regardless of the terrain. This is demonstrated by research observing that intraindividual differences in PO characteristics largely determined fast versus slow 1500 m cycling performances, with athletes able to adapt their pacing (i.e., the relative contribution of aerobic and anaerobic systems) depending on their physiological status (Hettinga et al., 2012). The ability to attune performance via PO feedback may be developed through experience, as indicated in Chapter 2 and by similar work (Massey et al., 2020), more experienced cyclists verbalised more PO-related thoughts than their counterparts. Therefore, it is understandable that the removal of this feedback would lead to a suboptimal performance by means of an overly conservative pacing strategy. Moreover, it may explain why performance was worse with the additional removal of PO (and speed) feedback in TTNoFB.

Following on, despite a worse performance when feedback was not presented, RPE and affect scores were similar or observably worse compared to when full feedback was provided. Moreover, the experimental trials were perceived as more taxing than in TTFull, as indicated by NASA Task Load Index scores. This in part suggests a reduction in economy alongside performance level in these experimental trials. Interestingly, similar or higher RPE and task load for similar or worse performance has been observed during endurance performance under conditions of high versus low mental fatigue, which is characteristically induced by performing taxing, prefrontal-dependent testing (Van Cutsem et al., 2017).

Research has presented inconsistent findings regarding cycling performance and pacing as a function of feedback availability. For instance, 20 km cycling TT performance was worse when participants were blinded to feedback in one study (Micklewright et al., 2010), but not in more recent research (Borg et al., 2020). One key difference between the two studies was the provision of end-point knowledge in the no-feedback condition in Borg et al. (2020), which was unavailable to participants in the Micklewright et al. (2010) study. However, another study observed no difference in 20 km TT performance despite blinding to end-point knowledge in the no-feedback condition (Smits et al., 2016). The authors here claim that prior experience allowed the cyclists to negate the lack of feedback and rely on interoceptive cues to pace the TT. The samples recruited across these studies appear homogeneous in using trained cyclists, so fitness status or experience is unlikely to account for the findings observed. Nonetheless, the present study is the first to test and observe a progressive reduction in performance as performance feedback and task knowledge are sequentially removed. Moreover, adding to the literature, it is the first investigation to observe this effect in TT performance over more challenging and varying terrain. Future work could seek avenues to improve the reflectiveness of real-world race scenarios, such as virtual reality (Neumann et al., 2018), and investigate the respective influences of key sources of feedback on endurance performance. This research could have applied value in tailoring the content of coaching, for instance, in attuning athlete’s decision-making to considering both workload (e.g., PO) and perceptual feedback (e.g., perceived exertion) in line with end-point knowledge. Indeed, inferring from their findings, Smits et al. (2016) recommended that athletes of all abilities pay greater attention to self-monitoring to develop experience-based awareness of effort in line with exercise duration, ultimately optimizing pacing as appropriate to exercise demands.

Prefrontal Haemodynamics and Executive Function

Concerning PFC activity, extrapolation of the trends observed to similar research and contemporary theory would be speculative. Moreover, using a single case study, it is not possible to make meaningful inferences regarding the impact of the independent variables (i.e., feedback provision) on PFC activity. However, general comparisons of findings to existing research holds some value for discussion. Most notably, as outlined in greater detail in Chapter 3, a meta-analysis has examined PFC activity as a function of exercise intensity (% of VO_{2peak}), observing a significant increase in O_2Hb from low to moderate-intensity, a plateau at moderate-to-hard intensities, before a decline at maximum, exhaustive intensities (Rooks et al., 2010). More relevant to this study, a recent review (De Wachter et al., 2021) has highlighted two studies that have investigated PFC haemodynamics during full effort self-paced endurance performance (Billaut et al., 2010; Santos-Concejero et al., 2015). In both studies, O_2Hb increased in the first half of the TT, before plateauing in the second half. O_2Hb increased and HHb decreased in the final 500 m during Billaut et al.'s study, suggesting near-exhaustion as a result of an end-spurt. A further study by Pires et al. (2016) observed an increase in PFC O_2Hb, HHb and tHb until 70% completion of a 4 km cycling TT. In line with the observations presented above, O_2Hb increased through to the 6 km mark. The plateau beyond 6 km suggests that a moderate-to-hard intensity was sustained through to the finish of the TT. No decline in O_2Hb during the final stages points to a self-regulation of effort to defend against homeostatic disturbance, therefore preserving cerebral oxygenation levels. This is most evident in the experimental trials where a significantly smaller end-spurt is observed compared to TTFull.

Although comparison to the review findings presented above is possible, the reviews predominately focused on research using ramped exercise protocols with no requirement for self-pacing, and therefore lack this key element of real-life racing scenarios. Two studies, detailed in Chapter 4, have investigated feedback provision on PFC activity using self-paced cycling TT protocols (Wingfield et al., 2018, 2019). In one study (Wingfield et al., 2019) using end-point deception, RPE was greater and O_2Hb values higher once deception was evident and participants were required to exercise longer than anticipated. The authors suggest that the PFC may regulate RPE to reduce the risk of catastrophic failure by driving down effort. In the present study, the higher tHb values in the final TT, and therefore greater regional blood volume to the PFC, could indicate greater engagement of executive functions to help self-regulate performance in the absence of performance feedback. The PFC is indirectly linked to motor control via the premotor area, therefore executive control may be involved in the appraisal of signalling from afferent feedback to self-regulate workload (Robertson & Marino, 2016). Interestingly, this occurred despite a worse performance, suggesting that cerebral perfusion differences cannot be solely explained by work capacity.

Theories concerning the PFC and exercise regulation, such as hypofrontality and lateralisation, are challenging to examine using self-paced protocols as they do not follow the tightly controlled block or event-related methodology observed in neurocognitive research (Herold et al., 2018). Compounding this, exercise pacing is a complex phenomenon influenced by physiological, psychological and social factors (Renfree & Casado, 2018). Nonetheless, the right dorsolateral PFC, a ROI in this case study, is thought to aid exercise tolerance by suppressing amygdala activation, thereby reducing the related stress response to prevent premature exercise cessation (Bigliassi & Filho, 2022). In the context of this study, it was anticipated that the pacing of hill climbs was key to optimal performance, and this would be yet more challenging through blinding to course knowledge and feedback information. In these most challenging climbing sections, higher levels of negative affect may be experienced by performers, leading to an increase in activation of the right dorsolateral PFC to regulate the associated stress response. Through expanding on this case study, we can investigate this proposition by going beyond the general notion of top-down control from the PFC (Ekkekakis, 2009). Such efforts would include the assessment of left and right PFC activity (e.g., relating to the control of approach and avoidance states, as aforementioned) to, for example, changes in task difficulty as demonstrated in this study. In addition, exercise-based research has yet to embrace techniques to directly assess PFC asymmetries, such as the laterality index used in this case study. Illustrating this point, no research presented in Chapter 4 directly compared left and right PFC activity during self-paced performance.

With respect to flanker task performance, the main observation in this current study was a facilitatory effect of TT completion on subsequent flanker task RT. This finding corroborates those presented in Chapter 2, where an improvement in flanker task RT was observed when completed less than 3 minutes following the completion of a full-effort 16 km cycling TT. This aligns with exercise-cognition literature that has observed a facilitatory effect of aerobic exercise on cognitive task performance requiring response inhibition and working memory, both during and after exercise bouts (Tomporowski, 2003). Despite no differences in cognitive performance between experimental conditions here, there is sufficient evidence presented and theoretical rationale outlined to warrant further exploration into the effect of feedback provision and task demands on PFC haemodynamics and cognitive performance related to self-regulated endurance performance. Lastly, in line with the psychobiological model (Marcora, 2010), if the PFC and executive control are indeed important for RPE regulation, any self-regulatory interventions could benefit performance through improving perceptual experience during exercise (Giles et al., 2018). Therefore, assessment of the cognitive and neuropsychological effects of interventions could provide insight into the mechanisms responsible for efficacy, adding support to their applied use.

Conclusion

Performance feedback appears important to the pacing of endurance performance. This is evident in the present case-study which found worse TT performance and economy when feedback provision was systematically removed. However, similar existing literature has observed inconsistent results, which possibly reflects the small number of studies conducted in this area and the difference in methodologies adopted (e.g., endpoint-knowledge provision). Future research should look to assess the relative contribution of performance feedback to endurance performance in realistic race-like simulations. Following on, findings concerning cerebral activity and cognitive testing are consistent with trends observed in exercise-based research. Although the findings of the present study do not provide clear support for cerebral or cognitive changes as a result of manipulating feedback provision, this study has argued for research to explore this possibility and has presented a methodology for doing so, successfully measuring cerebral haemodynamics using fNIRS in line with best-practice guidelines (Chapter 4). This research could have important implications for our understanding of pacing and the means to help guide athlete decision-making.

Chapter 6 An Exploratory Investigation into the Relationships Between Self-Regulation, Attentional Focus and Motivation in Naturalistic Endurance Training Settings

Abstract

Self-regulatory capacities have important implications for endurance performance success, including attentional control, maintaining motivation, and effective pacing. The primary objective of this research was to bring together relevant measures of self-regulation and cognition to explore their contribution to endurance exercise training and performance in real-world settings. Endurance performers (*n* = 42) were tasked with completing a series of state- and trait-based self-report measures via an online survey prior to and following a naturalistic endurance exercise training session of their choice. The survey captured training characteristics, alongside measures of sport-specific state and trait self-control, attentional focus, mind-wandering tendencies, and intrinsic motivation. Self-control would appear to decrease through performing endurance training, with perceived fatigue, training load and frustration levels predictive of post-training self-control. Moreover, higher trait self-control was positively related to the propensity to mind-wander during training. Additionally, this was borne out it in-practice, as participant’s self-control positively related to task-unrelated focus during training. Higher trait self-control was also positively related to training enjoyment and interest. Therefore, future work is needed to explore the cognitive, affective, and fatigue-related contributions to self-control and the unique demands that endurance performance places upon self-control resources. Moreover, given how attentional control is important for training (e.g., road safety) and performance (e.g., focusing on pacing goals), examining the relationship between self-control and attentional focus, and what factors (e.g., executive function) may underlie this, is warranted.

Introduction

Recent research has outlined how self-regulation is crucial to the decision-making processes and pacing of endurance performance (Hyland-Monks et al., 2018, i.e., Chapter 3). This review drew upon various research domains to argue that executive function underlies the top-down self-regulation of endurance exercise tasks. The review was in part influenced by extensive research by Brick and colleagues (Brick, MacIntyre, & Campbell, 2016) that investigated the importance of metacognitive processes to endurance performance. Specifically, the notion that metacognitive skills and experiences are key to an athlete's ability to form a representation of the task at hand to help guide decision-making and subsequent appraisal.

Brick and colleague's work (Brick, MacIntyre, & Campbell, 2016) has borne research using the think aloud (TA) protocol to capture and categorise within a theoretical framework the cognition of those completing endurance activities in naturalistic (e.g., Whitehead et al., 2017) and laboratory settings (e.g., Massey et al., 2020). Attentional focus predominantly related to thoughts defined as 'active self-regulation', and therefore the monitoring of key performance feedback (e.g., power output) and the means to regulate performance (e.g., motivational self-talk) to optimise pacing. This was in part supported by research presented in Chapter 2 observing that participants focused largely on self-regulation but also distance-related feedback. As outlined in Chapter 4, distance-related feedback is integrated by participants when self-regulating pacing behaviour in line with end-point knowledge (St. Clair Gibson et al., 2018). Indeed, distance-related thoughts often coincided with motivation-related thoughts. Furthermore, verbalisations relating to power output were more frequent among trained versus untrained participants, attesting to an attuned ability to focus and integrate key performance feedback to self-regulate effort. The research and findings presented in Chapter 2 provide valuable insight into how athlete's allocate attentional resources to pace performance within controlled laboratory environments. However, in this study, we aimed to take advantage of new and interesting methods to investigate the self-regulation, attention, and motivation of athletes that we first observed in Chapter 2 in more naturalistic/applied training and competitive settings.

Cognition

To date, the extant literature has observed that athletes of externally paced and strategic sports perform better compared to those of self-paced and static sports (such as endurance running and cycling) on measure of executive function (Ballester et al., 2019; Jacobson & Matthaeus, 2014; Krenn et al., 2018). However, as detailed in Chapter 3, endurance sport is ill-defined in these studies, and therefore this body of literature may undervalue the role of complex cognition to endurance performance success. As such, research has begun investigating more discrete differences in cognitive capacities among endurance athletes (e.g., by performance level). This allows one to assess the contribution of cognition more comprehensively to the unique psychological challenges of endurance sports.

Cona and colleagues tasked ultra-marathon runners with completing cognitive testing prior to an 80 km race (Cona et al., 2015, detailed in Chapter 3). In short, faster runners appeared to have better inhibitory control, displaying a superior ability to disregard interfering and distracting information. Following on, Belviranli et al. (2016) observed superior cognitive capacities in national-level orienteers and pentathletes versus healthy controls, and this was coupled with a higher plasma brain-derived neurotrophic factor (BDNF). BDNF performs several neuroprotective roles such as modulating neuronal survival and differentiation (Phillips et al., 2014). Endurance exercise has been observed to enhance BDNF levels and therefore neurotrophic pathways (Zoladz et al., 2008), presenting one causal mechanism that may explain Belviranli et al.'s (2016) and Cona et al.'s (2015) findings. Supporting Hyland-Monks and colleagues’ review (Hyland-Monks et al., 2018), this research points to cognitive capacities playing a key role in the regulation of endurance performance.

Attention

Research has begun to explore how executive function capacities may influence attentional focus and affective control in applied exercise performance settings. For instance, research has demonstrated that runner’s working-memory capacities were positively related to their propensity to engage in positive and prospective mind-wandering during an outdoor training run (Miś & Kowalczyk, 2021). Mind-wandering can be defined as a task-unrelated train of thought, occupying consciousness either through a deliberate (controlled) or spontaneous (uncontrolled) shift in attention (Giambra, 1995). Working-memory capacity was also positively associated with pleasant experiences and negatively with aversive aspects of training. Interestingly, a qualitative exploration of mind-wandering among students engaged in competitive sports has observed mind-wandering states to be more prevalent among endurance performers (Latinjak, 2018). However, despite the findings presented above, a review concluded that there is no convincing evidence linking working-memory capacities to sport expertise, or transference of working-memory training to sport performance (Furley & Wood, 2016). Although efforts to assess the benefits of differing attentional foci on performance are well established (Wulf, 2013), little attention has been paid to mind-wandering tendencies and how they may relate to participant and tasks dynamics during endurance sport.

Self-regulation

Several studies have created or adapted existing measures to capture self-regulatory capacities among endurance performers in training and competition settings. In keeping with the propositions detailed in Chapter 3, recent research has argued for a measure of self-regulation in endurance sport based on the premise that it is theoretically important for adherence to training schedules, race plans and pacing. The Endurance Sport-Specific Self-Efficacy Scale was developed with the aim of capturing performer's perceived control concerning the physical, technical, and psychological factors that are important to performance, demonstrating sound validity and reliability (Anstiss et al., 2018). The scale has recently been used to investigate the relationship between mental toughness, self-efficacy, and 100-mile ultra-marathon performance (Brace et al., 2020). Mental toughness subscales of confidence and control were significant predictors of self-efficacy. Although scores were not predictive of sport performance outcomes (ultra-marathon event placing and time), mental toughness scores were significantly higher for ultra-endurance athletes compared to scores observed for athletes across several other sports, including hockey, soccer, mixed martial arts, and tennis. Therefore, it is possible that the above measures capture important qualities to endurance performance success in applied settings, and therefore research is needed to further explore this.

Following on, recent research has adopted the Brief State Self-Control Capacity Scale to capture state-like fluctuations in perceived self-control strength during a shooting task (Englert, Dziuba, Wolff, & Giboin, 2021). Changes in performance were associated with perceived state self-control, which diminished over time. Interestingly, follow-up research has observed no deterioration in performance among elite shooters following prior self-control exertion (Englert, Dziuba, Giboin, & Wolff, 2021). Aligning with the observations of Belviranli et al. (2016) and Cona et al. (2015), these findings suggest that an athlete's competitive level could relate to their ability to preserve self-control resources during performance over time, although no direct comparison to less-able athletes is provided. However, such measures have yet to be used, or have been rarely adopted in empirical investigations into the psychology of endurance performance. Therefore, research has yet to draw together methods of measuring attentional control and self-regulation highlighted above. Such research would be highly valuable to the field of endurance sport given research has shown self-control capacities to be trainable. For instance, maximal graded cycling test performance was significantly improved following two weeks of isometric handgrip training (Bray et al., 2015). Although several brain-related adaptations are suggested to explain the findings, it is also suggested that a transference from the intervention task to cycling performance may relate to an increase in self-efficacy to withstand and better tolerate high-exertion levels (Bandura, 1977).

Aims

The primary objective of this research was to bring together relevant measures of self-regulation and cognition to explore their contribution to endurance exercise training and performance in real-world settings. More specifically, this research aimed to investigate how trait and state self-control measures, alongside mind-wandering tendencies related to attentional focus during endurance training. In addition, several other theoretically relevant factors were considered, including participant (e.g., motivation), training (e.g., intensity) and environmental variables (e.g., indoor vs. outdoor exercise). The flexible and self-report nature of the psychometric measures adopted allowed for this research to be conducted in real-world exercise training settings. Indeed, the generalisability of study findings is predicated on the representativeness of task design to the intended environment, in this case, exercise training and performance settings (Araújo et al., 2007). Moreover, the exploratory nature of this research will allow for the observation of behaviour in naturalistic settings to help inform more pointed research questions for future work to investigate (Bishop, 2008).

Method

Participants

54 participants who regularly take part in endurance sports were recruited to take part in the research via online and university campus advertisements. Unfortunately, a total of 12 possible participants did not complete both surveys to necessitate inclusion in the study. Participants (*n* = 42; female = 17) needed to be familiar with pacing and self-regulating endurance exercise as part of their training routines. Specifically, it was requested that participants were familiar with gauging effort in relation to performance feedback (e.g., power output and speed). In addition, participants were also required to have an endurance training history of no less than three years. Participants provided informed consent and the study was granted ethical approval by the relevant university institution prior to data collection. Participant characteristics, weekly training habits and experience are summarised in Tables 6.1 and 6.2.

Table 6.1 Mean (*SD*) for Participant’s Anthropometric Measures.

Participant characteristics	
Age (years)	39.31 (12.74)
Body weight (kg)	69.24 (12.48)
Height (cm)	173.21 (8.79)
Body Mass Index (kg/m^2)	22.96 (2.89)

Table 6.2 Mean (*SD*) for Participant’s Duration of Training Per Week and Total Years of Experience.

Exercise mode	**Time per week (hours)**	**Experience (years)**
Running (*n* = 31)	3.44 (1.75)	10.29 (10.99)
Cycling (*n* = 24)	5.83 (3.67)	14.33 (12.22)
Swimming (*n* = 8)	1.75 (1.16)	10.63 (12.82)

Design

The research required participants to complete a series of self-report measures prior to and following a naturalistic endurance exercise training session via an online survey (Online Surveys, Jisc: Bristol, UK).

Measures

Participant and Task Information

Participant information. A questionnaire was devised by the researcher to obtain basic demographic information and the mode, duration, frequency, and competitive level of participant's weekly endurance training and sport participation.

Training intentions. Participants were asked to describe the training they aimed to complete as part of the research. This included exercise mode and intensity, alongside the intended distance and duration of their training.

Trait Measures

Self-regulation. The Endurance Sport Self-Efficacy Scale (Anstiss et al., 2018) was used to assess participant's self-efficacy concerning their endurance sport activities. The scale has exhibited sound validity and reliability as a measure of self-efficacy among endurance athletes in Anstiss et al.'s (2018) research ($\alpha = .88$). The scale asks participants to "please rate your degree of confidence" from, "0, cannot do at all" to "100, completely certain" for items including "Maintain my concentration" and "Deal with feelings of effort and exertion". Higher scores indicate greater self-efficacy.

Mind-wandering. The Mindful Attention Awareness Scale (Seli et al., 2015) was used to assess tendencies toward both deliberate and spontaneous mind-wandering states during training. The scale exhibited sound validity and reliability as a measure of both deliberate ($\alpha = .88$) and spontaneous mind-wandering ($\alpha = .88$) in Seli et al.'s (2015) research. The scope of the scale was modified for the present research by asking participants to select a response that most accurately reflected "the nature of your mind-wandering when participating in your endurance sport(s)", ranging from "1 (rarely)" to "7 (a lot)" for items including "I allow my thoughts to wander on purpose" and "I find my thoughts wandering spontaneously". Higher scores indicate greater mind-wandering tendencies.

State Measures

Self-control. The Brief Self-Control Capacity Scale (Lindner et al., 2019) was used to measure state self-control. The scale has exhibited acceptable validity and reliability during sport performance across time (see Englert, Dziuba, Giboin, & Wolff, 2021; Englert, Dziuba, Wolff, & Giboin, 2021). The scale asks participants to select the most appropriate response to "how you feel at the moment", ranging from "0 (not true)" to "7 (very true)" for items including "I feel drained" and "I feel like my willpower is gone". Higher scores indicate greater self-control loss.

Attentional focus. Two single-item scale measures were developed by the researchers to capture participant's recall regarding their attentional focus during training. On completion of the training session, participants indicated their focus of attention during training on "Performance goals during the activity" and "Thoughts not relevant to the activity" on a scale ranging from "1 = never" to "5 = always".

Task demand. The National Aeronautics and Space Administration Task Load Index (NASA TLX; Hart & Staveland, 1988) was used to assess subjective workload across six single-item subscales: mental demand, physical demand, effort demand, performance success, frustration, and temporal demand. Each factor was able to contribute independent information about the source of workload for a given task. Moreover, the scale is more sensitive to experimental manipulations of workload compared to both a global rating and a combination of subscales. Participants were asked how "demanding the task was" in respect to each item on a scale ranging from "0, very low" to "20, very high". This score was multiplied by 5, resulting in a final score between 0 and 100 for each of the subscale items.

Fatigue. The single-item Rating of Fatigue Scale (Micklewright, St. Clair Gibson et al., 2017) was used to measure global subjective fatigue. The scale demonstrated sound face validity with divergence from perceived exertion, and significantly tracked physiological measures (e.g., heart rate) and physical activity levels (i.e., accelerometer data). The scale asked participants to "provide a rating that best reflects how fatigued you feel at this current moment", ranging from "0 (not fatigued at all)" to "10 (total fatigue and exhaustion - nothing left)". The scale is accompanied by visual and descriptive anchors.

Motivation. The Short Intrinsic Motivation Inventory (McAuley et al., 1989) was used to assess participant's intrinsic motivation for training. The scale has exhibited acceptable validity and reliability as a measure of effort/importance (α =

.72), interest/enjoyment (α = .78) and perceived competence (α = .83) during motor learning research (Abbas & North, 2018). The scale asked participants to rate statements concerning "how true they are to you in regard to your training session by selecting the most appropriate response", ranging from "1 (not at all true)" to "7 (very true)" for items including "This training session was fun to do" and "I would describe this training session as very interesting". Higher scores indicate greater intrinsic motivation.

Where relevant, please see references for full psychometric properties of the above scales. Table 6.3 details the internal consistencies for multi-item scales as calculated in the present study.

Table 6.3 Internal Consistencies.

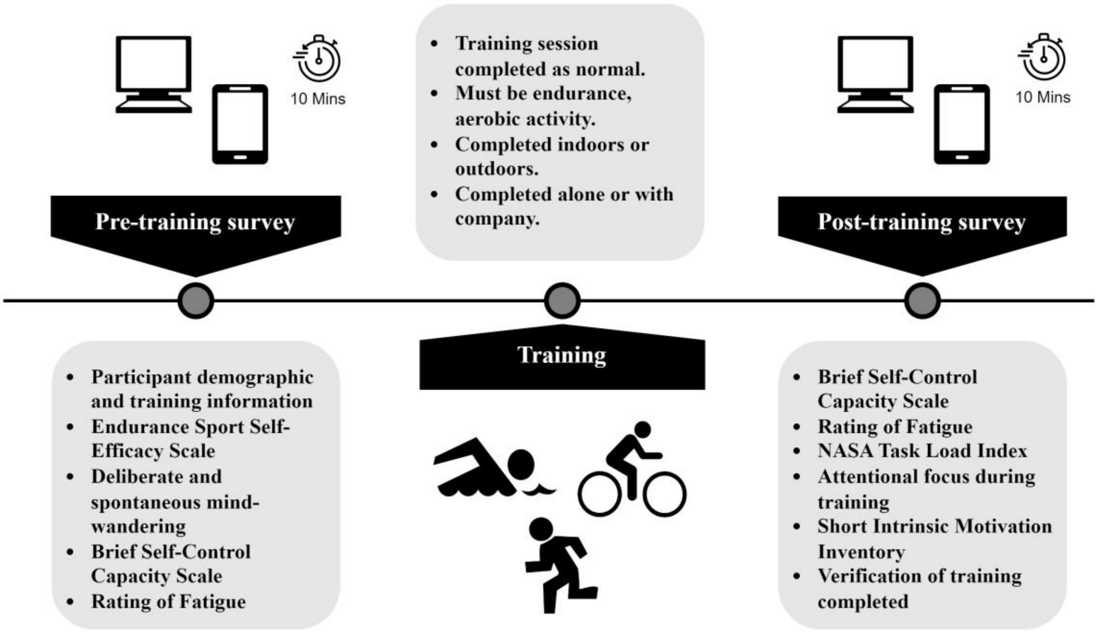
Scale	**Cronbach's alpha (α)**
Endurance Sport Self-Efficacy Scale	.94
Spontaneous mind-wandering[a]	.82
Deliberate mind-wandering[a]	.86
Brief Self-Control Capacity Scale (pre-training)	.78
Brief Self-Control Capacity Scale (post-training)	.64
Enjoyment and interest[b]	.82
Perceived competence[b]	.69
Importance and effort[b]	.76

Note. [a]Mindful Attention Awareness Scale; [b]Short Intrinsic Motivation Inventory.

Protocol

Participants were tasked with completing the above measures via an online survey (onlinesurveys.ac.uk) around a self-selected exercise endurance training session they completed as part of their normal endurance training routine. As such, the participant chose the training mode (e.g., running), whether they trained indoors or outdoors, and the type of training to be completed (e.g., interval session), ensuring that the session was defined as an endurance activity (i.e., a continuous effort that lasts for ≥ 75 seconds; McCormick et al., 2019). Participants were instructed to maintain normal activity, sleep patterns, and diet around the training session. Participants completed the measures above as part of a pre- and post-training survey, as outlined in Figure 6.1. Participants were instructed to complete the pre-training survey within 4 hours of initiating the session and the post-training survey immediately after, or as soon as possible following their training session. Estimated survey completion times were clearly communicated to participants to maximize full completion and engagement in both surveys. Upon completion of the pre-training survey, participants were encouraged to complete their intended training session and were given an indication of the post-training survey content. Following the post-training survey, participants were provided with debriefing information.

Figure 6.1 Experiment protocol.



The surveys were developed following the Ethical Guidelines for Internet-Mediated Research by The British Psychological Society (2017). Furthermore, established guidelines for building online experiments (Sauter et al., 2020) were followed to ensure survey content was clear and comprehensible, while keeping the survey as short as was reasonably possible. The survey was initially piloted on a small number of representative participants for the purpose of user feedback. Feedback derived from piloting informed the final development of the survey. This principally included changing the order in which scales were presented to improve the flow of the survey.

Data analysis

All ANOVA tests were performed using SPSS software (v.25). In line with established guidelines (Field, 2013), normality was analysed by visual inspection of distribution, skewness and kurtosis *z* scores, and Shapiro-Wilk statistics. Greenhouse-Geisser corrections were applied for violations of sphericity assumptions. *Post hoc* pairwise comparisons with Bonferroni-adjusted *p* values were conducted for significant *F*-ratios. Dunnett's T3 was used for pairwise comparisons when assumptions of equal sample sizes and variances were violated. Partial eta squared (ηp^2) is reported for main effects and interactions, and Cohen's *d* was calculated as appropriate to the research design (Lakens, 2013) and reported for *t*-tests and *post hoc* pairwise comparisons. All regression analyses were performed using GraphPad Prism software (v.9). Multicollinearity was assessed by VIF and tolerance scores, homoscedasticity via actual versus predicted residuals plots, and distribution and outliers by visual inspection of residuals plots, Shapiro-Wilk statistics and Cook's Distance calculations. Statistical significance was accepted at the probability criterion of $p < .05$ for all testing. Due to issues concerning the integrity of both training distance and duration measures (i.e., both measures being unanalogous), the authors decided to omit this data from the analysis.

Results

Descriptives statistics (*M*, *SD*) for both trait- and state-based study measures, pre- and post-training, are presented in Table 6.4 below.

Table 6.4 Mean (*SD*) for Study Measures.

Measure	**Pre-training (*M, SD*)**	**Post-training (*M, SD*)**
Trait-based measures		
Endurance Sport Self-Efficacy Scale	93.95 (15.67)	-
The Mindful Attention Awareness Scale		
Spontaneous mind-wandering	3.79 (1.38)	-
Deliberate mind-wandering	4.44 (1.46)	-
State-based measures		
Brief Self-Control Capacity Scale	2.90 (1.12)	2.50 (0.85)
Rating of Fatigue Scale	4.00 (1.95)	4.67 (2.27)
Attentional focus		
On-task	-	3.62 (0.96)
Off-task	-	2.10 (1.23)
NASA-TLX		
Physical demand	-	62.02 (22.85)

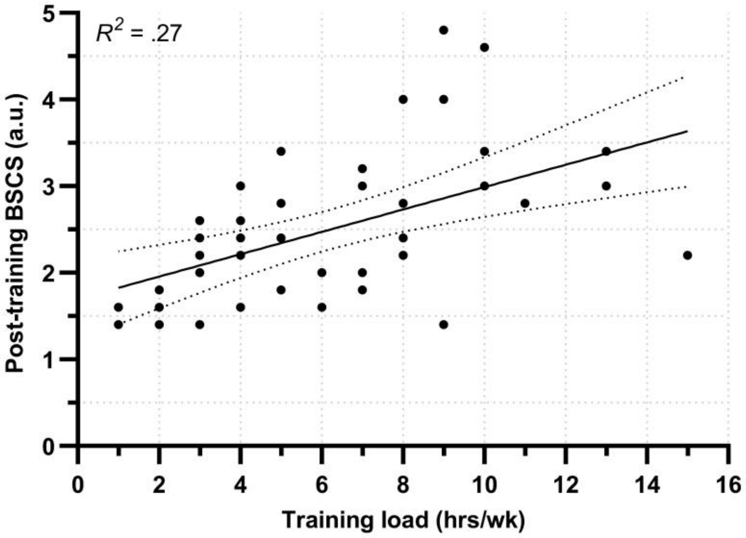
Mental demand	-	41.79 (24.52)
Effort demand	-	66.31 (19.73)
Performance success	-	79.29 (21.14)
Frustration	-	18.57 (20.28)
Temporal demand	-	42.26 (26.53)
The Short Intrinsic Motivation Inventory		
Effort and importance	-	5.18 (1.28)
Interest and enjoyment	-	4.95 (1.27)
Perceived competence	-	5.45 (1.03)

Note. NASA-TLX = National Aeronautics and Space Administration Task Load Index.

Self-Control

A multiple linear regression was performed to assess the factors related to Brief Self-Control Capacity Scale scores post-training. The overall regression model was significant, $F(5, 36) = 10.38$, $p < .001$, $R^2 = .59$. Significant predictors were weekly training load (β = 0.12, $p < .001$; Figure 6.2), post-training frustration (β = 0.02, $p = .001$) and post-training Rating of Fatigue (β = 0.14, $p = .007$). Mental demand and physical demand of the training were non-significant predictors (both $p > .05$). Brief Self-Control Capacity Scale scores were significantly lower post-training ($M = 2.50$, $SD = 0.85$) compared to pre-training ($M = 2.90$, $SD = 1.12$), $t(41) = 2.19$, $p = .034$, $d_z = 0.34$.

Figure 6.2 Training Load and Post-Training Brief Self-Control Capacity Scale.

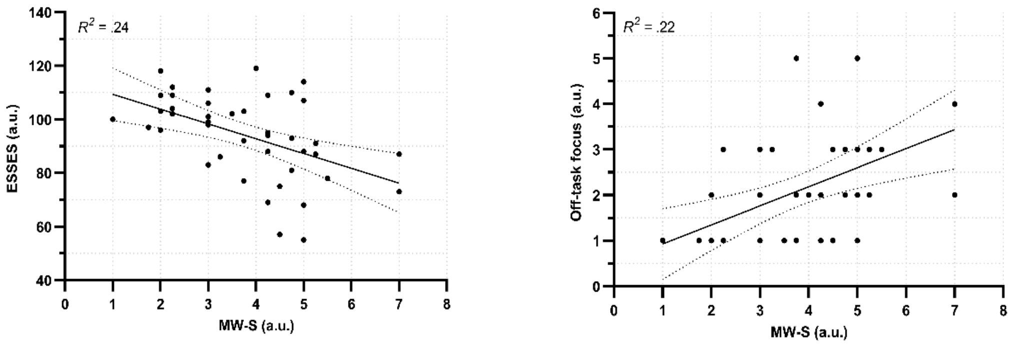


Note. Dotted lines represent 95% confidence interval. BSCS = Brief Self-Control Capacity Scale.

Attention Focus

A multiple linear regression was performed to assess whether trait-based mind-wandering tendencies related to Endurance Sport Self-Efficacy Scale scores. The overall regression model was significant, $F(2, 39) = 6.19$, $p = .005$, $R^2 = .24$. The only significant predictor was spontaneous mind-wandering ($\beta = -5.08$, $p = .01$; Figure 6.3). Deliberate mind-wandering was a non-significant predictor ($p > .05$). Additionally, a simple linear regression between spontaneous mind-wandering and task unrelated thoughts during training was significant, $F(1, 40) = 11.50$, $p = .002$, $R^2 = .22$. Spontaneous mind-wandering significantly predicted task-unrelated thoughts during training ($\beta = 0.42$; Figure 6.3).

Figure 6.3 Spontaneous Mind-Wandering and Endurance Sport Self-Efficacy Scale (left); Spontaneous Mind-Wandering and Task-Unrelated Focus (right).



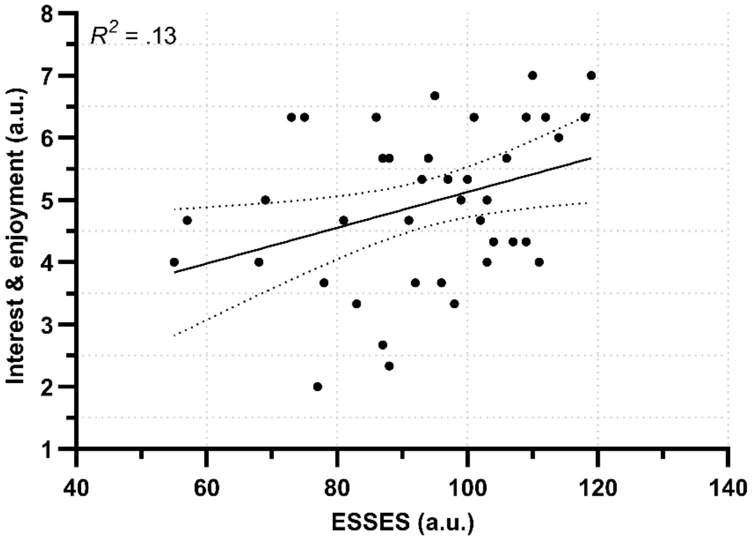
Note. Dotted lines represent 95% confidence interval. MW-S = spontaneous mind-wandering, ESSES = Endurance Sport Self-Efficacy Scale.

A significant main effect was observed for training type on self-reported goal-focus during training, $F(2, 36) = 4.52$, $p = .02$, $\eta p^2 = .20$. A significantly greater focus on goals was observed when participants completed high-intensity training ($M = 4.10$, $SD = 0.74$) compared to low-intensity endurance training ($M = 3.16$, $SD = 0.90$, $p = .03$, $d_s = 1.11$). In addition, a significantly greater focus on goals was observed for participants who chose to train indoors ($M = 4.08$, $SD = 0.90$) versus outdoors ($M = 3.43$, $SD = 0.94$), $t(40) = 2.06$, $p = .046$, $d_s = 0.70$. However, no other significant effects were observed for self-reported goal-focus and task unrelated thoughts during training as a result of training type or training environment (all p values > .05).

Motivation

Multiple linear regressions were performed to assess the factors related to the perception of effort and importance, interest and enjoyment, and perceived competence as sources of intrinsic motivation concerning the training completed. Concerning effort and importance, the overall regression model was significant, $F(3, 38) = 4.46$, $p = .009$, $R^2 = .26$. The only significant predictor was perceived physical demand of the training ($\beta = 0.03$, $p = .01$). Mental demand and effort demand were non-significant predictors (both $p > .05$). Concerning interest and enjoyment, the overall regression model was significant, $F(4, 37) = 3.89$, $p = .01$, $R^2 = .30$. Significant predictors were Endurance Sport Self-Efficacy Scale scores ($\beta = 0.04$, $p = .006$; Figure 6.4), task unrelated focus during training ($\beta = -0.45$, $p = .01$) and spontaneous mind-wandering ($\beta = 0.41$, $p = .03$). Deliberate mind-wandering was a non-significant predictor ($p > .05$). Concerning perceived competence, the overall regression model was significant, $F(2, 39) = 18.98$, $p < .001$, $R^2 = .49$. Significant predictors were perceived performance success ($\beta = 0.02$, $p < .001$) and post-training frustration ($\beta = -0.02$, $p = .005$).

Figure 6.4 Endurance Sport Self-Efficacy Scale and Interest and Enjoyment.



Note. Dotted lines represent 95% confidence interval. ESSES = Endurance Sport Self-Efficacy Scale.

A significant main effect was observed for training type on self-reported effort and importance of training, $F(2, 36) = 3.53$, $p = .04$, $\eta p^2 = .16$. A significantly greater effort and importance was attributed to high-intensity training ($M = 5.97$, $SD = 0.64$) compared to low-intensity endurance training ($M = 4.75$, $SD = 1.44$, $p = .01$,

$d_s = 0.98$). However, no other significant effects were observed for effort and importance, interest and enjoyment, or perceived competence as a result of training type or training environment (all p values > .05).

Task Demands

A significant main effect was observed for training type on self-reported mental demand, $F(2, 36) = 5.33$, $p = .009$, $\eta p^2 = .23$, physical demand, $F(2, 36) = 5.06$, $p = .01$, $\eta p^2 = .22$, effort demand, $F(2, 36) = 6.46$, $p = .004$, $\eta p^2 = .26$, and temporal demand of training, $F(2, 36) = 16.50$, $p < .001$, $\eta p^2 = .48$. Key *post-hoc* comparisons are presented below in Table 6.5. However, no other significant effects were observed for Rating of Fatigue, post-training frustration, or perceived performance success as a result of training type or training environment (all p values > .05).

Table 6.5 *Post-Hoc* Comparisons for Task Demands.

Measure	**Main effect**	***Post-hoc* comparisons (*M*, *SD*)**	**Effect size (d_s)**
Mental demand	Training type**	High intensity (60.50, 25.87) > low intensity (32.11, 20.90)**	1.25
Physical demand	Training type*	High intensity (77.50, 6.35) > low intensity (55.00, 23.75)*	1.14
Effort demand	Training type**	High intensity (80.00, 11.79) > low intensity (57.89, 18.88)**	1.31
		Tempo, threshold (74.50, 18.02) > low intensity (57.89, 18.88)^{ns}	0.89
Temporal demand	Training type***	High intensity (64.50, 21.79) > low intensity (26.58, 16.59)***	2.05
		Tempo, threshold (59.00, 21.32) > low intensity (26.58, 16.59)***	1.77

Note. ^{ns}non-significant, *$p < .05$, **$p < .01$, ***$p < .001$.

Discussion

In the present study, participants were tasked with completing a series of self-report measures prior to and following a post-exercise endurance training session. The principal aim of this research was to uniquely bring together measures of self-regulatory capacities, attentional processes, and motivational quality to establish how these factors influence the psychology of endurance performance in real-world training settings. The key findings will be summarised and then discussed in relation to existing literature and theory. In addition, given the exploratory nature of the work, recommendations for future research, and the value this work would represent to advancements in endurance sport, will be provided.

Self-control

Participant's rating of post-training self-control was significantly lower than pre-training levels, indicating a higher self-control loss post-training. To the researcher's knowledge, no research has directly measured self-control over time in an endurance performance setting. This finding is in contrast to a loss of self-control over time that has been observed in research concerning motor performance. For instance, self-control levels were found to decline over time for elite and sub-elite shooters between shooting task intervals (Englert, Dziuba, Wolff, & Giboin, 2021). Moreover, shooters who reported lower levels of self-control strength performed worse. Compared to elite shooters, sub-elite shooters displayed greater deterioration in shooting performance and self-control over time. This research was followed by more experimental work to assess self-control and elite shooter's performance following prior mental exertion (Englert, Dziuba, Giboin, & Wolff, 2021). However, no change in self-control levels or performance was observed as a result of prior mental fatigue versus control conditions.

These findings would align with resource-based models of self-control (Baumeister, 2002). The key concept of such models is that self-control resources are limited; akin to a working muscle, such resources are finite and expended over time, ultimately leading to a state of 'ego-depletion'. However, differences in self-control levels and performance as a result of experience but not mental fatigue suggest there is some nuance to the conditions in which self-control relates to performance. One explanation proposed by Englert, Dziuba, Giboin, and Wolff (2021) is a higher degree of automatization of task-specific processing demands for elite athletes, resulting in less self-control costs to further self-regulatory efforts and performance. Indeed, expert versus novice comparisons reveal practice-induced cortical adaptations that require less attentional demand and less cognitive interference concerning motor planning and execution (Hatfield et al., 2004).

However, how such theories relate to highly automated sports like running and cycling is unclear. In these fields, little conclusive evidence has been presented to suggest improved efficiency in more experienced or higher-performing athletes that can be separated from any aerobic fitness-related adaptations (Ettema & Lorås, 2009). The research of Cona et al. (2015) and Belviranli et al. (2016) highlights a possible superior prefrontal dependent cognition in superior endurance performers, which may relate to adaptations to neurotrophic pathways. Furthermore, Martin et al. (2016) observed greater resistance to mental fatigue effects on time-trial performance in more highly trained cyclists. A causal mechanism for this result, as suggested by Martin et al. (2016), is an adaptation to the anterior cingulate cortex in trained persons. This area of the brain is implicated in effortful cognitive control (Bush et al., 1998) and perception of effort (Williamson et al., 2002). Therefore, the above research provides alternative theories for the 'strengthening' of self-control resources through practice at the level of the brain. Using the metacognitive framework (Brick, MacIntyre, & Campbell, 2016) from an applied perspective, these improvements may relate to enhanced active self-regulation (e.g., power output adjustments) in line with internal sensations (e.g., perceived fatigue) and competitor behaviour (e.g., an opponent starting to move ahead). Future work could investigate the self-control levels of endurance performers over time at various levels of expertise (Pauw et al., 2013); moreover, to establish a possible causal mechanism, following prior mental exertion. Such work could highlight the value in monitoring self-control levels across an athlete's competition, training, and other commitments.

Following on, it was found that both Rating of Fatigue and training load are significant predictors of self-control post-training. Both predictors were positively related to self-control. This would suggest that both accumulative and acute contributions to sensations of fatigue play a role in perceptions of self-control. Fatigue has become a variable of interest for researchers looking to expand on resource-based models of self-control (Baumeister, 2002). In one such study, participants were asked to complete muscular endurance exercise to exhaustion under conditions of high and low mental fatigue (Graham et al., 2017). A mediation analysis indicated self-control exertion increased fatigue, which in turn led to reduced task self-efficacy and performance. In turn, a mechanistic link has been suggested between neurophysiological changes resultant from prolonged exertion of self-control and interoceptive sensations of fatigue (Holroyd, 2016). From a motivational perspective, these aversive sensations are thought to signal the rising cost of further engagement of self-control to help inform a cost–reward analysis either toward or away from further control application (Wolff & Martarelli, 2020). Future research could explore whether endurance performer’s self-control levels track both acute and chronic fatigue, whether this be derived from physical or perceptual measures. If such links are established, these findings could help athletes and coaches manage cognitively demanding elements of their schedule, including training, to minimise their effects on fatigue levels.

Furthermore, task frustration was also found to significantly predict post-training self-control levels. The two variables were positively related. It is important to note that task frustration involved asking participants how “insecure, discouraged, irritated, stressed, and annoyed were you?” during training. Therefore, this measure captures emotional quality in the moment. Pertinently, research has observed worse performance on a demanding and frustrating problem-solving task completed after participants were challenged to suppress their emotion while watching an emotive movie (Baumeister et al., 1998). Therefore, it is possible that the requirement to regulate affective state during participant’s training sessions may have been deleterious to self-control. Moreover, such regulatory efforts may have been impacted by affective changes related to a hypofrontality effect during training. The reticular activating hypofrontality (RAH) model (Dietrich & Audiffren, 2011) proposes a downregulation in prefrontal areas, and therefore executive control, in line with training duration and intensity. This could, for example, present a challenge in the reappraisal of interoceptive cues (e.g., through motivational self-talk) to help resist the urge to stop or reduce effort when highly fatigued. Therefore, alongside prior mental exertion as described above (Englert, Dziuba, Giboin, & Wolff, 2021; Graham et al., 2017; Martin et al., 2016), future work could explore whether affective regulation reduces self-control capacities and subsequent exercise performance. Psychological strategies to regulate emotion in sport are long established (Lane et al., 2012). If such strategies are effective at preserving self-control capacities, this may in turn benefit self-efficacy and performance (Graham et al., 2017).

Attentional Focus

Participant’s spontaneous mind-wandering tendencies during training significantly predicted scores on the Endurance Sport Self-Efficacy Scale. The two variables were negatively related. It is important to note that the Endurance Sport Self-Efficacy Scale places a strong emphasis on self-regulatory capacities. For instance, the scale asks how confident one is in their ability to “maintain [their] concentration” and “manage [their] thoughts during events”. Indeed, Anstiss and colleagues state that one’s self-efficacy concerning their ability to “control and manage exercise induced sensations and intrusive thoughts and emotions is likely to be an important factor in understanding and enhancing endurance performance” (p. 181, Anstiss et al., 2018). Therefore, the results would appear to suggest a link between participant’s tenancies to mind-wander involuntarily during training and their self-regulatory capacities as they pertain to endurance performance. In addition, spontaneous mind-wandering significantly predicted participant’s task unrelated focus during the training session completed. The two variables were positively related. Therefore, this research is unique in finding a possible link between spontaneous mind-wandering and self-regulation that is borne out in-practice. That is, those that are more likely to spontaneously mind-wander during training reported a greater task unrelated focus during the training. From an applied perspective, measuring athlete’s mind-wandering tendencies could be used to determine those who may benefit from strategies to maintain task focus and avoid distractions, such as instructional self-talk (Hatzigeorgiadis & Galanis, 2017).

Miś and Kowalczyk's (2021) work points to a possible link between mind-wandering tendencies, working memory capacity, and affective regulation during running training. Given the self-regulatory nature of the Endurance Sport Self-Efficacy Scale, it is plausible that working memory capacity, a domain of top-down executive control (Miyake et al., 2000), overlaps with the abilities measured by the scale. Therefore, it is possible that working memory is important to affective and attentional control during training. If true, it contradicts findings that suggest no relationship between working memory and sport expertise (Furley & Wood, 2016). In turn, it would support the findings of research looking more specifically at endurance performance and executive function highlighted earlier (Belviranli et al., 2016; Cona et al., 2015; Martin et al., 2016). This difference may relate to the inadequate categorisation of endurance sports in the extant literature (e.g., Krenn et al., 2018) which do not capture the dynamical (Renfree & Casado, 2018) and psychological (Venhorst et al., 2018) components of endurance performance. This may have hindered attempts to explore the cognitive demands of endurance sports that are important for success. Furthermore, given that research has demonstrated cognitive reappraisal is effective in the regulation of affective state and perceived exertion during running performance (Giles et al., 2018), future research could investigate the link between executive function and self-regulatory capacities, and how they relate to endurance performance and efficiency.

Following on, participant's attentional focus was influenced by the type of training performed and the environment it was completed in. Participants reported a greater focus on their training goals when completing high-intensity compared to low-intensity endurance training. In addition, a greater focus on training goals was reported when the training was completed in an indoor versus outdoor environment. Although not compared to lower intensity exercise, previous work utilising TA has suggested a predominant focus on active self-regulation during full-effort, high-intensity time-trial performance (Massey et al., 2020; Whitehead et al., 2017, 2018). Exercising at full capacity is the ultimate test of a performer's ability to manage their resources effectively. This is demonstrated by participant's thought processes from the research presented in Chapter 2. For instance, the need to maintain a high workload (e.g., "I'm pushing really hard") in the face of discomfort (e.g., "legs are very sore!"), aided by self-regulatory strategies (e.g., "just relax and stay in control") and motivational self-talk (e.g., "12 km's done, great effort!"). These cognitions may be underpinned by the cerebral perturbations described above as part of the RAH model (Dietrich & Audiffren, 2011). As exercise exceeds the ventilatory threshold, the performer must contest with the hypofrontality of self-control regions of the brain to maintain top-down control of pacing. Conversely, at lower intensities, the performer has more voluntary control of attentional focus and may switch between a task-related and task-unrelated focus of attention (Hutchinson & Tenenbaum, 2007). This notion is also reinforced by participants perceiving high-intensity training as more mentally demanding than low-intensity training.

An alternative explanation for the lower task-focus for low-intensity, endurance training may relate to its longer duration and less demanding nature. Indeed, participants reported a higher perceived physical demand for high-intensity versus low-intensity training. This reduced task engagement is possibly explained by boredom effects; that is, an aversive state induced by unsuccessful engagement in the task at hand (Eastwood et al., 2012). Training has been reported as boredom-inducing even for professional athletes (Velasco & Jorda, 2020). This is especially pertinent when one considers the repetitive and often prolonged duration of aerobic endurance training. These effects may have been more pronounced for participants who completed training indoors. Indeed, a systematic review found that exercise in natural environments was associated with greater positive engagement and mood profile versus indoor exercise (Thompson Coon et al., 2011). Moreover, boredom may result from a challenge-skill imbalance where the task is perceived as underchallenging (Pekrun et al., 2010), such as low-intensity training in the present study. It is also possible for the converse to be true, that a prolonged activity is very challenging to self-control resources in terms of maintaining task-focus. The findings of the present study support the former notion, as participants rated high-intensity training more effort-demanding than those completing low-intensity, endurance training. However, no significant findings were observed for task unrelated thoughts as a function of training type and environment. Therefore, the propositions provided above are only partially supported by the findings. To date, surprisingly little work has investigated how the nature of training (e.g., task intensity and duration) impacts self-regulatory capacities and attentional focus in applied settings, including task engagement and boredom, so future work could explore this. Investigating the antecedents of these aversive states will provide vital information for the development of strategies to combat them. Such research is timely given that those who experienced boredom were more likely to suffer from an ‘action crisis’ (i.e., considerable mental difficulties in achieving one’s goals) during ultra-marathon competition (Weich et al., 2022).

Motivation

The only significant predictor of perceived effort and importance was perceived physical demand of the training completed. The two variables were positively related. In addition, participants attributed a greater effort and importance to high-intensity training compared to low-intensity, endurance training. This is not surprising given that participants rated high-intensity training as more physically and mentally demanding, and more effortful to complete. This would suggest an intrinsic link between the effort and importance one places on training, and the physical workload and nature of the training completed. Firstly, it is pertinent to note that motivation is key to contemporary thinking concerning the psychology of endurance performance (e.g., Marcora, 2010). Indeed, an improvement in 10 km time-trial cycling performance was observed through using motivational self-talk compared with neutral self-talk (Barwood et al., 2015), suggesting that the motivational quality of the intervention was key. Following on, the findings are perhaps illustrative of a misperception that high-intensity training is most important to one's endurance training goals. Recent research has shown that regardless of how exercise training is structured (i.e., pyramidal or polarized), endurance performers effectively improved endurance surrogates and performance via completing the majority of their training in 'Zone 1' (between 77-81%), described as intensities below the first ventilatory threshold (Filipas et al., 2022). This is also reflective of the training regimes of elite-level cross-country skiers, as over 90% of their training was characterised as below the first lactate threshold (Tønnessen et al., 2014). However, without detailed information regarding participant's respective disciplines, it is not possible to accurately compare their training to the findings above. In addition, the nature of sub-elite training may also be influenced by practical barriers, such as time constraints, making it difficult to complete low-intensity training at the required volume. Nonetheless, this is something to be mindful of for coaches, practitioners, and performers alike, and future research could explore sub-elite performer's training regimes and the factors involved in developing them.

Significant predictors of interest and enjoyment were Endurance Sport Self-Efficacy Scale scores, spontaneous mind-wandering, and task unrelated focus. Both self-efficacy and mind-wandering were positively related to interest and enjoyment, whereas task-unrelated focus was negatively related. These findings may be explained by the performer's ability to regulate both performance and attentional focus during training, leading to better perceived task engagement. As aforementioned, those with a perceived capability to effectively self-regulate performance and affective state may be better able to maintain goal-directed behaviour in the face of adversity (Brick, MacIntyre, & Campbell, 2016). In an applied sense, this could mean the effective management of workload (e.g., maintain pace at the desired intensity) and affective state (e.g., emotional valence) through sufficient attention on one's objective and away from unwanted thoughts (e.g., sensations of fatigue leading to self-doubt). This process could be aided by proven coping strategies to cognitively reappraise the sensations of fatigue to ultimately guide decision-making in line with one's goals (e.g., to resist the urge to slow down). Indeed, those equipped with psychological interventions (e.g., implementation intentions) reported better stress controllability post-exercise versus control participants (Meijen et al., 2022). Furthermore, mind-wandering tendencies positively correlating with enjoyment and interest is intriguing given that previous research has observed a link between mind-wandering and working-memory capacity in runners (Miś & Kowalczyk, 2021). Working memory can be defined as the capacity to retain a small amount of information relevant to an on-going task active in one's mind (Furley & Wood, 2016). Therefore, the findings may reflect the capacity to mind-wander during performance without hindering the engagement in pursuing one's goals. Little attention has been dedicated to mind-wandering states and endurance performance, so future research could explore propensities to mind-wander and the function this serves for endurance performers.

Significant predictors of perceived competence were perceived performance success and post-training frustration. Whilst performance success positively related to competence, frustration was inversely related to performance. Therefore, it would appear that perceived competence is derived from both perceived task success (e.g., achieving one's training goals) and how frustrating the participant found the experience (e.g., experiencing an action crisis, such as an injury). In practice, this demonstrates the importance of striking a balance between setting achievable yet challenging training goals. Recent research has shown that goal difficulty shares a linear relationship with persistence (Lee et al., 2015). However, this relationship breaks down for extremely difficult goals. This curvilinear relationship is mediated by affect (e.g., satisfaction in achieving a difficult goal) and the expectancy of achieving one's goal (i.e., chance of success). Future work could explore whether this relationship between goal difficulty and commitment is shared in respect to endurance training and the challenges that it presents.

Limitations and Future Directions

One limitation to the present study is sample size. A variety of guidelines have been put forth for determining minimum sample size for regressions. One method is to use a participant-to-variable ratio, which typically range from 15-40 participants recommended per explanatory variable used (Dancey & Reidy, 2017).

Moreover, Tabachnick & Fidell (2013) have presented a formula for determining sample sizes for regressions, $N \geq 50 + 8M$ (where ‘M’ is the number of explanatory variables used). Therefore, despite being an exploratory project, caution should be exercised when analysing the findings from this research, as results can be overly optimistic (i.e., a higher likelihood of type I errors) when smaller sample sizes are used (Dancey & Reidy, 2017). Related to the above, a further drawback to the present study is the attrition rate of participants from the pre- to post-training survey (22%). This threatens the generalisability and external validity of the findings through a reduction in sample size possibly influenced by systematic differences in participant characteristics (Zhou & Fishbach, 2016). Although guidelines for internet-mediated research were followed, further survey instruction that prewarns participants of what to expect and features an appeal-to-consciousness (e.g., “drop-out may compromise data quality”) has been shown to significantly reduce drop-out rates (Zhou & Fishbach, 2016). Likewise, data analysis suffered from missing data or incorrect completion of the survey by participants. This may reflect the difficulty in conducting research at distance without the ability to supervise study participation. Therefore, the survey may have benefitted from the inclusion of periodical instruction or attention checks, as suggested by Sauter et al. (2020). Future research should take these extra measures to minimize study attrition and preserve the quality of data collection. However, as Sauter et al. (2020) note, such remedies can present their own selective biases. Lastly, although this study aimed to examine self-selected training in naturalistic settings, a limitation of this approach is the lack of control concerning the nature of participant’s training. Future research could prescribe different types of training (e.g., low vs. high intensity) to be completed in different environments (e.g., indoors vs. outdoors) so more valid and reliable comparisons can be made.

Conclusion

This research aimed to investigate how self-regulatory processes relate to endurance performer’s experience (i.e., attention, motivation, and effort) in their natural training routines. Warranting investigation, existing literature has seldom investigated these processes to understand the factors contributing to pacing behaviour outside of contrived laboratory settings. Firstly, it seems plausible to suggest that self-control capacity is a limiting factor concerning endurance performance. However, how existing theory relates to endurance performance remains unclear, with several competing theories primed for investigation. Therefore, future work to explore the cognitive, affective, and fatigue-related contributions to self-control effects on endurance performance is warranted, alongside the role of performer's characteristics (e.g., expertise level). Moreover, a possible link exists between self-control capacities, mind-wandering tendencies, and task focus during training. Interestingly, these same factors were predictive of task enjoyment and interest. In addition, task focus appears to be influenced by training demands and the environment. As optimizing decision-making and pacing is crucial to performance, further explorations into athlete's attentional focus tendencies could be advantageous for the development of strategies to aid self-regulatory efforts and task engagement, particularly for those prone to mind-wandering, completing strenuous training regimes, or exercising in unstimulating conditions (e.g., indoors). Furthermore, a greater importance was placed on high-intensity relative to low-intensity training, which calls for research into sub-elite training regimes and the reasons behind their development to help guide training in line with one's goals.

Chapter 7 General Discussion

In this final chapter, for each research theme, I will outline the aims, methodology, and salient findings. I will also detail the theoretical and practical implications of these findings, and the directions that future research could take. Following this, a personal reflection on my learnings will be provided. Here, I will detail the adversities I faced when completing this work and how such learnings will positively impact my future research endeavours.

Think Aloud and Thought Processes

With a burgeoning field of research adopting think aloud (TA) as a method to capture the thought processes of endurance performers (Massey et al., 2020; Samson et al., 2017; Whitehead et al., 2017, 2018), this study was the first to assess in earnest the feasibility of TA methodology to capture thought processes during self-paced endurance performance, alongside what thought processes captured, in conjunction with measures of cognition and psychophysiology, contribute to our understanding of pacing behaviour. To achieve these aims, 16 cyclists (8 trained, 8 untrained) were tasked with completing a 16 km lab-based TA and No TA time-trial (TT). In addition, affective state and Rating of Perceived Exertion (RPE) were measured during, and response inhibition (i.e., flanker task) was measured pre- and post-exercise.

Promisingly, TA did not appear to compromise exercise performance or pacing. Likewise, no significant difference in perceptual experience was reported by participants. Moreover, flanker task performance, and therefore response inhibition capacities were not found to significantly differ across the experimental trials. It should also be noted that the analysis accounted for TA prevalence (i.e., frequency of verbalisation) as a potential confound on these results. Therefore, it would appear that TA is feasible to use during endurance exercise performance without undue interference (i.e., reactivity). Pertinently, this finding would contrast with that outlined in a review of TA use across a variety of performance domains that observed a small-to-moderate effect size for reactivity (Fox et al., 2011). This study was the first to directly compare TA to control conditions in self-paced endurance performance. Given the novelty of the results observed, future studies are needed to replicate these findings. Regardless of the results, this prudence will allow for more informed conclusions to be drawn from research using TA to capture endurance performer’s thought processes moving forward.

Largely reflecting nascent literature (Massey et al., 2020; Whitehead et al., 2018), distance- and motivation-related verbalisations were most prevalent. Furthermore, these themes became increasingly more frequent as the finish line approached. This suggests that self-regulatory interventions are most useful in the more difficult, latter stages of a race, as previous research has suggested (Barwood et al., 2015), and that end-point knowledge becomes more salient in gauging effort in anticipation of an end-spurt (St. Clair Gibson et al., 2018). Thought processes became less outwardly orientated as the TT progressed, possibly reflecting affective changes and cerebral perturbations, principally the downregulation of lateral areas of the prefrontal cortex (PFC) to preserve more vital brain regions around the ventilatory threshold (Dietrich & Audiffren, 2011), as a transition from a positive to negative affective experience occurs (Ekkekakis et al., 2011). Now with a growing body of literature using TA, a greater understanding of the nature of endurance performer's thoughts can help inform coaching, for instance, in the development of pacing strategies and deployment of psychological strategies (Whitehead et al., 2018). Specifically, athletes can maximise the benefits of psychological strategies by using them in the final stages of endurance events when fatigue levels and the need to resist the urge to stop or slow down are most pressing, and affective regulation is most difficult. Moreover, this approach could be individualised to a given athlete based on their thought processes during training or performance.

Despite the feasibility and usefulness of TA highlighted above, there are considerations to be heeded before inferring from observations derived from the methodology. Firstly, assessing the feasibility of TA is challenging as it may confer benefits to performance (e.g., increased self-monitoring of pacing), but also limit performance through interference (i.e., reactivity). As such, these pros and cons are difficult to disentangle. Adding to this, recent work has observed benefits to both cycling performance and economy through using TA (Whitehead et al., 2022). However, this study used TA in conjunction with functional near-infrared spectroscopy (fNIRS) to measure PFC activity, which could help disentangle TA effects, if present, and what may underlie them. Therefore, future work should look to explore TA use in tandem with other measures of cognition. Furthermore, there is a question of what TA truly captures. Unconscious and subconscious influence over pacing may be left unaccounted for by TA (Micklewright, Kegerreis et al., 2017).

Therefore, measures of non-explicit cognition, such as eye tracking (Massey et al., 2020) may help address this. In addition, does TA merely reflect the stimuli available in the environment? This is particularly pertinent for research conducted in laboratory settings. Therefore, efforts to bridge the gap to real-world applied settings are needed, which may come in the shape of virtual reality (Neumann et al., 2018) or more field-based research (Whitehead et al., 2017).

With TA research into endurance exercise still in its infancy, there are several further opportunities for future work to learn and build on existing literature and the work conducted here. Comparatively few differences in TA content were observed between trained and untrained populations in this research relative to the existing literature (Massey et al., 2020; Whitehead et al., 2018). Indeed, this may relate to small differences in participant characteristics or task demands, as stated in Chapter 2. Nonetheless, further steps could be taken to better define participant populations to investigate expert versus novice comparisons. To this end, obtaining absolute and relative VO_{2max}, alongside peak aerobic power output (PO) would allow one to classify participants against well-established criteria outlined for cyclists (Pauw et al., 2013). Robustly conducted research using these criteria could be highly valuable as cerebral oxygenation is better preserved among aerobically trained individuals during high-intensity exercise (Rooks et al., 2010), which might have implications for cognition and the verbalisation of thought processes during endurance exercise. Possible future directions for research involving TA are summarised in Table 7.1.

Table 7.1 Possible Future Directions for Investigating the Psychology of Self-Paced Endurance Performance.

Think Aloud	**Executive Function and fNIRS**	**Self-Regulation**
• More robust expert vs. novice comparisons.	• Prospective study designs to assess cognition and endurance performance.	• Fatigue and affective contributions to self-control capacities.
• More immersive environments (e.g., Zwift[a]).	• Best-practice use of fNIRS to explore neurocognitive mechanisms of pacing.	• Attentional control, mind-wandering states and their effects on performance.

• Combine with other neurocognitive measures (e.g., fNIRS).	• To investigate specific functions of the PFC in regulating endurance performance (e.g., by expanding Chapter 5 research).	• Training characteristics and their effects on attentional focus and motivation.

Note. [a]Online virtual cycling and running software.

Lastly, it is also useful to personally reflect on your work as a researcher to learn from the adversities you have faced. With a purported ‘replication crisis’ in the field of psychology (Maxwell et al., 2015) and concerns regarding the integrity of research in sport and exercise sciences (Schweizer & Furley, 2016), the need for comprehensive prior planning of research is clearer than ever. Despite performing an *a priori* power calculation for the present research, experimental studies are often underpowered to detect small-to-medium effects (Schweizer & Furley, 2016). This may have been the case for hypotheses beyond the question of simple reactivity in the present research, as more variables (e.g., trained vs. untrained comparisons) are factored into the calculation. Indeed, trends toward a decline in cognitive performance following the TA condition may have been statistically significant with greater power. Remedies suggested to mitigate these issues are largely beyond the capacities of a PhD researcher, such as collaborative efforts from multiple investigators (Maxwell et al., 2015). However, with the benefit of hindsight, more careful consideration in project development would be prudent in future. Considerations should include the methodology (e.g., sample size required) and means to conduct the work (e.g., personnel involved in data collection) within a reasonable timeframe.

fNIRS and Executive Function

As TA reveals the conscious thought processes related to pacing behaviour, other methodologies are being adopted to glimpse the underlying mechanisms concerning the self-regulatory properties of the brain during performance. Indeed, there is a growing interest in the neuropsychology of pacing and endurance performance, ranging from reviews covering cerebral oxygenation patterns during incremental exercise (Rooks et al., 2010), PFC response as a function of exercise characteristics (De Wachter et al., 2021), and the feasibility of fNIRS to investigate the exercise–cognition relationship (Herold et al., 2018). However, these reviews do not grapple with the self-regulatory processes that govern the pacing of endurance performance (i.e., executive control), and how existing means (i.e., fNIRS) could be used to investigate these processes. Given that pacing is a dynamical process that requires the balancing of various competing interests (Renfree & Casado, 2018), self-paced exercise and the PFC, implicated in the decision-making required, was of particular interest. Therefore, via a narrative review, Chapter 3 sought to explore the self-regulation of endurance performance through the lens of executive functioning. Subsequently, via a scoping review, Chapter 4 sought to assess both the methodology and findings of research using fNIRS over the PFC during self-paced endurance performance. In Chapter 5, this groundwork was used to undertake an experimental investigation into the importance of feedback integration to endurance performance, using measures of TT performance, psychophysiology, cognition, and PFC haemodynamics.

In Chapter 3, an argument for the importance of cognitive processes to the self-regulation of endurance performance is presented. Previous thinking has focused on metacognitive and attentional processes without addressing the role of executive functions *per se* (e.g., Brick, MacIntyre et al., 2016). Cross-sectional comparisons of sport types have not presented a compelling case for the importance of cognition to sporting success (e.g., Krenn et al., 2018), however more pointed research has observed greater inhibitory control (Cona et al., 2015) and resistance to mental fatigue in trained athletes (Martin et al., 2016), and better optimized pacing in line with adolescence development (Micklewright et al., 2012). Therefore, more prospective study designs are needed to assess the predictive power of cognition to endurance performance success (Kalén et al., 2021), which could be a highly valuable new tool for talent ID programs. Indeed, recent research has called for talent ID programmes to consider self-regulatory skills (Elferink-Gemser & Hettinga, 2017). Moreover, there is some early evidence that endurance and mental fatigue training improves exercise tolerance (Marcora et al., 2015), therefore the training of executive control could be a new frontier for athletes to gain an advantage over opponents, but more research is needed.

In Chapter 4, the first comprehensive review into PFC measurement via fNIRS during self-paced performance revealed the importance of cerebral oxygen availability to aerobic exercise performance, with working capacity reduced under conditions of hypoxia (Bourdillon et al., 2014) or bolstered under conditions of hyperoxia (Nielsen et al., 1999). By extension, further research has shown some positive effects on performance through dietary interventions to enhance cerebral oxygenation (Fan et al., 2018; Shannon et al., 2017) and PFC transcranial direct-current stimulation (tDCS; Machado et al., 2019), however evidence is limited at this nascent stage. Of greater relevancy here, research has also taken a more psychological approach by assessing the manipulation of exercise task demands on pacing behaviour and PFC activity. PFC activity has been observed to reflect the anticipatory processes driving pacing, with cortical changes observed dependent on end-point knowledge (Radel et al., 2017; Wingfield et al., 2019). Moreover, PFC activity correlated with workload (i.e., PO) feedback only when this was presented to participants (Wingfield et al., 2018). These findings have important theoretical implications for our understanding of the importance of the PFC to pacing, which in turn holds value for applied practice. For instance, cerebral haemodynamic measurement could be used to investigate the brain related mechanisms responsible for the effectiveness of self-regulatory interventions. Indeed, research has observed changes in affective response and the frontal cortex through using imagery during exercise above the ventilatory threshold (Tempest & Parfitt, 2013). If mechanisms of intervention effectiveness are established, interventions can be fine-tuned to target these mechanisms, possibly enhancing their effectiveness (McCormick et al., 2015). Consequently, it should hold that such neuropsychological evidence adds weight to dissemination efforts with relevant stakeholders in applied sport settings.

One way of maximizing our understanding of the neuropsychology of pacing is to ensure best-practice use of fNIRS technology concerning both data capture and analysis methods, also subject to review in Chapter 4. Across the 17 reviewed studies using fNIRS during self-paced exercise, most adopted commonplace and feasible best practice guidelines, including collecting baseline data and measuring both oxygenated haemoglobin (O_2Hb) and deoxygenated haemoglobin (HHb). Conversely, only one study reported efforts to address data artefacts, which is widely adopted in established domains of fNIRS use (Orihuela-Espina et al., 2010). In a field relatively new to adopting the technology, it is especially important that researchers set a high standard for work that succeeds their efforts. In addition, only 10 of 17 studies specified a region or regions of interest, and no studies made specific hypotheses concerning the function of the PFC in performance regulation.

Such efforts are needed if we are to test theories such as hypofrontality (Dietrich & Audiffren, 2011) and lateralization (Ekkekakis, 2009). Moreover, research in sport and exercise science has typically used relatively small samples of participants (Schweizer & Furley, 2016), therefore, it is crucial that data derived from such studies is valid and reliable. Finally, from personal experience, conducting fNIRS exercise-based research and adhering to all the above practices in a safe and effective manner is challenging for a single researcher to undertake. Therefore, for future research, it is worth considering the complexity of the project and the resources at hand. If such considerations and best practice guidelines are adopted, fNIRS holds real promise as a tool for increasing our understanding of the psychology of endurance performance.

The research outlined above inspired the experiment presented in Chapter 5. This case study sought to examine the influence of feedback provision and course knowledge on cycling TT performance over a realistic, race-like simulation with an undulating course. These sources of information were sequentially removed from subsequent TT’s completed in the hope of understanding their importance *in absentia*. When no feedback was provided, TT performance was slower and more conservative pacing was adopted during the climbing sections. Although previous research has examined feedback effects on endurance performance (Borg et al., 2020; Micklewright et al., 2010; Smits et al., 2016), this study was unique in doing so using a challenging hilly course that is more reflective of real-world road cycling, and therefore more demanding of self-regulatory resources. Higher O_2Hb and total haemoglobin (tHb) values were observed in the partially and fully blinded TT’s in several prefrontal areas, possibly indicating a greater engagement of the PFC to help regulate performance in the absence of feedback. However, given that limited research has investigated PFC haemodynamics and feedback blinding or deception (Wingfield et al., 2018, 2019), interpretation of the findings in reference to the current evidence base is limited. Hence, an expansion of this case study into a full experiment is warranted to help grow our understanding of the PFC and its contribution to endurance performance, and how this information can inform psychological strategies or ergogenic means. Possible future directions for research involving cognition and fNIRS are summarised in Table 7.1.

Self-Regulation in Real-World Settings

The preceding chapters have outlined the importance of self-regulatory capacities to endurance performance. To achieve this, studies have typically used controlled laboratory experiments such as those presented in Chapters 2 and 5. However, the cognition, attentional focus and decision-making processes captured in contrived, laboratory-based experiments may differ to those observed in applied settings. Therefore, the primary objective of this chapter was to bring together relevant measures of self-regulation and cognition to explore their contribution to endurance training and performance in real-world settings. To accomplish this objective, endurance performers were recruited to complete a series of state- and trait-based self-report measures via an online survey prior to and following an endurance training session of their choice.

The findings revealed that state-based self-control loss was significantly higher post-training versus pre-training levels, aligning with findings from motor control research (Englert, Dziuba, Giboin, & Wolff, 2021; Englert, Dziuba, Wolff, & Giboin, 2021). Training load, fatigue, and task frustration were predictive of self-control losses post-training, highlighting possible affective and fatigue-related mechanisms. Therefore, future research to explore self-control losses in endurance sport training and competition, and how fatigue and affective states may contribute to this, is warranted. If self-control loss has deleterious effects on performance (Hunte et al., 2021), for instance, on the point of volitional exercise termination (Robertson & Marino, 2016), interventions to reduce the impact of perceived fatigue and improve affective regulation hold promise in preserving self-control capacities in applied settings.

Following on, trait self-control negatively related to spontaneous mind-wandering tendencies during training. Furthermore, this finding was reinforced in practice, as mind-wandering positively related to task-unrelated focus during training. This suggests a possible link between self-regulatory capacities and attentional control, aligning with previous work linking working memory with mind-wandering during training among runners (Miś & Kowalczyk, 2021). From an applied perspective, greater attentional control and emotional regulation would be advantageous to avoiding aversive states that negatively affect performance, ranging from boredom (Velasco & Jorda, 2020) to choking (Hill et al., 2010). This may have been evidenced in this research, as participants scoring higher in trait self-control reported greater enjoyment and interest in their training. Therefore, research investigating attentional control and mind-wandering states, and how they may relate to affective experiences and performance, is needed. As with the TA research above, this work will need to reflect real-world sports training and competition, whether this is achieved through further field work or technology (i.e., virtual reality).

The nature of training would also appear to impact attentional and motivational processes. A greater on-task focus and importance of training was reported for high- versus low-intensity training. This finding is reinforced by those presented in Chapter 2 highlighting that cyclist's thought processes largely revolved around performance feedback and self-regulatory efforts. This is hypothesised to reflect goal-directed cognition to regulate or sustain exercise under high workload (Robertson & Marino, 2016). Conversely, at lower intensities, the greater voluntary control of attentional focus (Hutchinson & Tenenbaum, 2007) may explain the lower reported task-focus observed. These conditions may be antecedents to boredom and subsequent aversive events (Weich et al., 2022). Although research has investigated attentional focus strategies on performance (e.g., Schücker et al., 2016), little research has explored the unique demands of endurance training (e.g., repetition) on attentional focus (e.g., off-task focus) and its effects (e.g., boredom and its implications), so future work could explore this.

As demonstrated in this research, online and remote methods provided an opportunity to explore the psychology of endurance performance in naturalistic training settings. However, these methods present several challenges to data collection, most notably here, a high drop-out rate between the pre- and post-training surveys. To better manage these limitation in future investigations, measures can be adopted to minimise participant attrition. For instance, providing sufficient details regarding study demands (Zhou & Fishbach, 2016) and the inclusion of periodic reminders of survey instructions (Sauter et al., 2020). Such research designs present a valuable opportunity to collect larger sample sizes than typically observed for experimental work in sport and exercise psychology (Schweizer & Furley, 2016). Moreover, if conducted with appropriate rigour, this should not come with undue costs to the quality of data collection. Therefore, online and distance methods hold great promise for future research, with ideas suggested above and summarised in Table 7.1.

Personal Reflections

Although I have reflected on the research conducted above, I will dedicate this brief section to some personal reflections that will help me moving forward, and may also help other postgraduates in a similar position. The first thing I would like to reflect on is the skills I have developed along the way. This includes the ability to conduct mixed methods psychophysiological research in a sports setting, alongside the ability to analyse, interpret and explain the data produced. Coming from a background in psychology, acquiring these new skills in a partly new field was a substantial learning curve, but one I am proud to have endured. Likewise, I have also improved my writing skills to better summarise and synthesise my research in a concise fashion. These skills will be invaluable for me as I move on to the next chapter of my academic career.

Following on, completing this PhD has shaped my overall approach to academia. Coming into the process, I was very meticulous and a little idealistic with what I would like to achieve. In being so, I underestimated the challenges that conducting research at this level would present. This is all without considering truly unforeseen events, such as a global pandemic. Although I still hold myself to high standards, I have developed a more stoic and pragmatic approach that has helped me problem-solve more effectively and adjust to setbacks more resiliently. I believe this approach was needed when the pandemic forced a shift in plans from an experimental approach to research that could be conducted in the field. Relatedly, through my studies, I have become more cognizant of the need to separate my studies and work from the rest of my life and the other things I care about. There is no panacea for establishing the optimal work-life balance, but putting time aside for family and friends, and to exercise, read, or to listen to my favourite albums all certainly helped.

Conclusion

This thesis has used and scrutinised the capacity of new methods and measures to help develop our understanding of pacing behaviour. Firstly, in Chapter 2, TA as a means to capture endurance performer’s thought processes was subject to scrutiny and was observed to not unduly interfere with exercise performance. Therefore, insights gained concerning performer's cognitions could be used in good faith for the development and tailoring of psychological interventions by practitioners, athletes, and coaches alike. In Chapter 4, fNIRS as a means to measure cerebral haemodynamics during self-paced endurance performance was compared to established best-practice guidance, highlighting gaps in adherence to ensure data recording and analysis integrity. This adherence will be vital to maximising confidence in findings from this body of literature, including the research presented in Chapter 5. Moreover, this body of literature has observed cerebral oxygenation to be a limiting factor on exercise performance (Chapter 4) and the PFC to be important to the self-regulation of endurance performance and pacing (Chapters 3 & 4). Finally, in Chapter 6, a broader perspective was adopted to explore self-regulatory processes and how they relate to cognitive, affective, and motivational processes during real-world endurance training. This remotely conducted research highlighted the relationship between novel measures of self-control capacities and attentional control during endurance performance, with the potential for future work to use these methods and measures to answer more clearly defined working hypotheses. Collectively, this thesis lends support to new and developing methods in the shape of TA and fNIRS, and applied research using novel measures to further our understanding of the self-regulatory processes underlying the pacing of endurance performance.

References

Abbas, Z. A., & North, J. S. (2018). Good-vs. Poor-Trial Feedback in Motor Learning: The Role of Self-Efficacy and Intrinsic Motivation Across Levels Of Task Difficulty. *Learning and Instruction, 55,* 105-112. https://doi.org/10.1016/j.learninstruc.2017.09.009

Abbiss, C. R., & Laursen, P. B. (2005). Models to Explain Fatigue During Prolonged Endurance Cycling. *Sports Medicine, 35*(10), 865-898. https://doi.org/10.2165/00007256-200535100-00004

Abbiss, C. R., & Laursen, P. B. (2008). Describing and Understanding Pacing Strategies During Athletic Competition. *Sports Medicine, 38*(3), 239-252. https://doi.org/10.2165/00007256-200838030-00004

Abbiss, C. R., Peiffer, J. J., Meeusen, R., & Skorski, S. (2015). Role of Ratings of Perceived Exertion During Self-Paced Exercise: What are We Actually Measuring? *Sports Medicine, 45*(9), 1235-1243. https://doi.org/10.1007/s40279-015-0344-5

Alvarez, J. A., & Emory, E. (2006). Executive Function and the Frontal Lobes: A Meta-Analytic Review. *Neuropsychology Review, 16*(1), 17-42. https://doi.org/10.1007/s11065-006-9002-x

Amann, M., Proctor, L. T., Sebranek, J. J., Eldridge, M. W., Pegelow, D. F., & Dempsey, J. A. (2008). Somatosensory Feedback From the Limbs Exerts Inhibitory Influences on Central Neural Drive During Whole Body Endurance Exercise. *Journal of Applied Physiology, 105*(6), 1714-1724. https://doi.org/10.1152/japplphysiol.90456.2008

Amann, M., Proctor, L. T., Sebranek, J. J., Pegelow, D. F., & Dempsey, J. A. (2009). Opioid-Mediated Muscle Afferents Inhibit Central Motor Drive And Limit Peripheral Muscle Fatigue Development in Humans: Intrathecal Fentanyl and Central Motor Drive. *The Journal of Physiology, 587*(1), 271-283. https://doi.org/10.1113/jphysiol.2008.163303

Angus, S. D. (2014). Did Recent World Record Marathon Runners Employ Optimal Pacing Strategies? *Journal of Sports Sciences, 32*(1), 31-45. https://doi.org/10.1080/02640414.2013.803592

Anstiss, P. A., Meijen, C., Madigan, D. J., & Marcora, S. M. (2018). Development and Initial Validation of the Endurance Sport Self-Efficacy Scale (ESSES). *Psychology of Sport and Exercise, 38,* 176-183. https://doi.org/10.1016/j.psychsport.2018.06.015

Araújo, D., Davids, K., & Passos, P. (2007). Ecological Validity, Representative Design, and Correspondence Between Experimental Task Constraints and Behavioral Setting: Comment on Rogers, Kadar, and Costall (2005). *Ecological Psychology, 19*(1), 69-78. https://doi.org/10.1080/10407410709336951

Balagué, N., Hristovski, R., Aragonés, D., & Tenenbaum, G. (2012). Nonlinear Model of Attention Focus During Accumulated Effort. *Psychology of Sport and Exercise, 13*(5), 591-597. https://doi.org/10.1016/j.psychsport.2012.02.013

Ballester, R., Huertas, F., Pablos-Abella, C., Llorens, F., & Pesce, C. (2019). Chronic Participation in Externally Paced, but not Self-Paced Sports is Associated With the Modulation of Domain-General Cognition. *European Journal of Sport Science, 19*(8), 1110-1119. https://doi.org/10.1080/17461391.2019.1580318

Bandura, A. (1977). *Social learning theory*. Englewood Cliffs, NJ: Prentice Hall

Barker, J. B., Mellalieu, S. D., McCarthy, P. J., Jones, M. V., & Moran, A. (2013). A Review of Single-Case Research in Sport Psychology 1997-2012: Research Trends and Future Directions. *Journal of Applied Sport Psychology, 25*(1), 4-32. https://doi.org/10.1080/10413200.2012.709579

Barwood, M. J., Corbett, J., Wagstaff, C. R. D., McVeigh, D., & Thelwell, R. C. (2015). Improvement of 10-km Time-Trial Cycling With Motivational Self-Talk Compared With Neutral Self-Talk. *International Journal of Sports Physiology and Performance, 10*(2), 166-171. https://doi.org/10.1123/ijspp.2014-0059

Baumeister, R. F. (2002). Ego Depletion and Self-Control Failure: An Energy Model of the Self's Executive Function. *Self and Identity, 1*(2), 129-136. https://doi.org/10.1080/152988602317319302

Baumeister, R. F., Bratslavsky, E., Muraven, M., & Tice, D. M. (1998). Ego Depletion: Is the Active Self a Limited Resource? *Journal of Personality and Social Psychology, 74*(5), 1252-1265. https://doi.org/10.1037/0022-

3514.74.5.1252

Baumeister, R. F., & Heatherton, T. F. (1996). Self-Regulation Failure: An Overview. *Psychological Inquiry, 7*(1), 1-15. https://doi.org/10.1207/s15327965pli0701_1

Baumeister, R. F., Vohs, K. D., & Tice, D. M. (2007). The Strength Model of Self-Control. *Current Directions in Psychological Science, 16*(6), 351-355. https://doi.org/10.1111/j.1467-8721.2007.00534.x

Beilock, S. L., Wierenga, S. A., & Carr, T. H. (2002). Expertise, Attention, and Memory in Sensorimotor Skill Execution: Impact of Novel Task Constraints on Dual-Task Performance and Episodic Memory. *The Quarterly Journal of Experimental Psychology Section A, 55*(4), 1211-1240. https://doi.org/10.1080/02724980244000170

Belviranli, M., Okudan, N., Kabak, B., Erdoğan, M., & Karanfilci, M. (2016). The Relationship Between Brain-Derived Neurotrophic Factor, Irisin and Cognitive Skills of Endurance Athletes. *The Physician and Sportsmedicine, 44*(3), 290-296. https://doi.org/10.1080/00913847.2016.1196125

Bernards, J., Sato, K., Haff, G., & Bazyler, C. (2017). Current Research and Statistical Practices in Sport Science and a Need for Change. *Sports, 5*(4), 87. https://doi.org/10.3390/sports5040087

Bigliassi, M., & Filho, E. (2022). Functional Significance of the Dorsolateral Prefrontal Cortex During Exhaustive Exercise. *Biological Psychology, 175,* 108442. https://doi.org/10.1016/J.BIOPSYCHO.2022.108442

Billat, V., Lepretre, P. M., Heugas, A. M., Laurence, M. H., Salim, D., & Koralsztein, J. P. (2003). Training and Bioenergetic Characteristics in Elite Male and Female Kenyan Runners. *Medicine & Science in Sports & Exercise*, *35*(2), 297-304. https://doi.org/10.1249/01.MSS.0000053556.59992.A9

Billaut, F., Davis, J. M., Smith, K. J., Marino, F. E., & Noakes, T. D. (2010). Cerebral Oxygenation Decreases but Does not Impair Performance During Self-Paced, Strenuous Exercise. *Acta Physiologica*, *198*(4), 477-486.

https://doi.org/10.1111/j.1748-1716.2009.02058.x

Bini, R. R., Diefenthaeler, F., & Mota, C. B. (2010). Fatigue Effects on the Coordinative Pattern During Cycling: Kinetics and Kinematics Evaluation. *Journal of Electromyography and Kinesiology, 20*(1), 102-107. https://doi.org/10.1016/j.jelekin.2008.10.003

Bishop, D. (2008). An Applied Research Model for the Sport Sciences. *Sports Medicine, 38*(3), 253-263. https://doi.org/10.2165/00007256-200838030-00005

Blanchfield, A. W., Hardy, J., De Morree, H. M., Staiano, W., & Marcora, S. M. (2014). Talking Yourself Out of Exhaustion: The Effects of Self-Talk On Endurance Performance. *Medicine and Science in Sports and Exercise, 46*(5), 998-1007. https://doi.org/10.1249/MSS.0000000000000184

Boksem, M. A. S., & Tops, M. (2008). Mental Fatigue: Costs and Benefits. *Brain Research Reviews, 59*(1), 125-139. https://doi.org/10.1016/j.brainresrev.2008.07.001

Borrell, J. A., Fraser, K., Manattu, A. K., & Zuniga, J. M. (2022). Laterality Index Calculations in a Control Study of Functional Near Infrared Spectroscopy. *Brain Topography, 6*(2), 210-222. https://doi.org/10.21203/RS.3.RS-2093217/V1

Borg, D. N., Osborne, J. O., Stewart, I. B., Costello, J. T., Headrick, J., McMaster, B. S., Borg, S. J., & Minett, G. M. (2020). The Availability of Task-Specific Feedback Does not Affect 20 Km Time Trial Cycling Performance or Test-Retest Reliability in Trained Cyclists. *Journal of Science and Medicine in Sport, 23*(8), 758-763. https://doi.org/10.1016/j.jsams.2019.12.024

Borg, G. A. V. (1982). Psychophysical Bases of Perceived Exertion. *Medicine & Science in Sports & Exercise, 14*(5), 377-381. https://doi.org/10.1249/00005768-198205000-00012

Bourdillon, N., Fan, J.-L., & Kayser, B. (2014). Cerebral Oxygenation During the Richalet Hypoxia Sensitivity Test and Cycling Time-Trial Performance in Severe Hypoxia. *European Journal of Applied Physiology, 114*(5), 1037-1048. https://doi.org/10.1007/s00421-014-2835-8

Brace, A. W., George, K., & Lovell, G. P. (2020). Mental Toughness and Self-Efficacy of Elite Ultra-Marathon Runners. *PLOS ONE, 15*(11), e0241284. https://doi.org/10.1371/journal.pone.0241284

Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). Explaining the many varieties of working memory variation: dual mechanisms of cognitive control. In A. R. Conway, C. Jarrold, M. J. Kane, A. Miyake, and J. Towse (Eds.), *Variation in working memory* (pp. 76-106). New York: Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195168648.003.0004

Bray, S. R., Graham, J. D., & Saville, P. D. (2015). Self-Control Training Leads to Enhanced Cardiovascular Exercise Performance. *Journal of Sports Sciences, 33*(5), 534-543. https://doi.org/10.1080/02640414.2014.949830

Brick, N. E., Campbell, M. J., Metcalfe, R. S., Mair, J. L., & Macintyre, T. E. (2016). Altering Pace Control and Pace Regulation: Attentional Focus Effects During Running. *Medicine & Science in Sports & Exercise, 48*(5), 879-886. https://doi.org/10.1249/mss.0000000000000843

Brick, N. E., Fitzpatrick, B. L., Turkington, R., & Mallett, J. C. (2019). Anticipated Task Difficulty Provokes Pace Conservation and Slower Running Performance. *Medicine & Science in Sports & Exercise, 51*(4), 734-743. https://doi.org/10.1249/mss.0000000000001844

Brick, N. E., MacIntyre, T. E., & Campbell, M. J. (2014). Attentional Focus in Endurance Activity: New Paradigms and Future Directions. *International Review of Sport and Exercise Psychology, 7*(1), 106-134. https://doi.org/10.1080/1750984x.2014.885554

Brick, N. E., MacIntyre, T. E., & Campbell, M. J. (2016). Thinking and Action: A Cognitive Perspective on Self-Regulation During Endurance Performance. *Frontiers in Physiology, 7*. https://doi.org/10.3389/fphys.2016.00159

Brisswalter, J., Collardeau, M., & René, A. (2002). Effects of Acute Physical Exercise Characteristics on Cognitive Performance. *Sports Medicine, 32*(9), 555-566. https://doi.org/10.2165/00007256-200232090-00002

British Psychological Society. (2021). *Ethical Guidelines for Internet-Mediated Research.* https://www.bps.org.uk/guideline/ethics-guidelines-internet-mediated-research

Brownsberger, J., Edwards, A., Crowther, R., & Cottrell, D. (2013). Impact of Mental Fatigue on Self-paced Exercise. *International Journal of Sports Medicine, 34*(12), 1029-1036. https://doi.org/10.1055/s-0033-1343402

Budgett, R. (1998). Fatigue and Underperformance in Athletes: The Overtraining Syndrome. *British Journal of Sports Medicine, 32*(2), 107-110. https://doi.org/10.1136/bjsm.32.2.107

Bush, G., Whalen, P. J., Rosen, B. R., Jenike, M. A., McInerney, S. C., & Rauch, S. L. (1998). The Counting Stroop: An Interference Task Specialized for Functional Neuroimaging-Validation Study With Functional MRI. *Human Brain Mapping, 6*(4), 270-282. https://doi.org/10.1002/(sici)1097-0193(1998)6:4<270::aid-hbm6>3.0.co;2-0

Campos, H. O., Drummond, L. R., Rodrigues, Q. T., Machado, F. S. M., Pires, W., Wanner, S. P., & Coimbra, C. C. (2018). Nitrate Supplementation Improves Physical Performance Specifically in Non-Athletes During Prolonged Open-Ended Tests: A Systematic Review and Meta-Analysis. *British Journal of Nutrition, 119*(6), 636-657. https://doi.org/10.1017/s0007114518000132

Chacko, S. C., Quinzi, F., De Fano, A., Bianco, V., Mussini, E., Berchicci, M., Perri, R. L., & Di Russo, F. (2020). A Single Bout of Vigorous-Intensity Aerobic Exercise Affects Reactive, but not Proactive Cognitive Brain Functions. *International Journal of Psychophysiology, 147*, 233-243. https://doi.org/10.1016/j.ijpsycho.2019.12.003

Chee, M. W. L., Venkatraman, V., Westphal, C., & Siong, S. C. (2003). Comparison of Block and Event-Related fMRI Designs in Evaluating the Word-Frequency Effect. *Human Brain Mapping, 18*(3), 186-193. https://doi.org/10.1002/hbm.10092

Christensen, L. O. D., Johannsen, P., Sinkjaer, T., Petersen, N., Pyndt, H. S., & Nielsen, J. B. (2000). Cerebral Activation During Bicycle Movements in Man. *Experimental Brain Research, 135*(1), 66-72.

https://doi.org/10.1007/s002210000493

Clingman, J. M., & Hilliard, D. V. (1990). Race Walkers Quicken Their Pace by Tuning in, Not Stepping Out. *The Sport Psychologist*, *4*(1), 25-32. https://doi.org/10.1123/tsp.4.1.25

Cohen-Gilbert, J. E., & Thomas, K. M. (2013). Inhibitory Control During Emotional Distraction Across Adolescence and Early Adulthood. *Child Development*, *84*(6), 1954-1966. https://doi.org/10.1111/cdev.12085

Cona, G., Cavazzana, A., Paoli, A., Marcolin, G., Grainer, A., & Bisiacchi, P. S. (2015). It's a Matter of Mind! Cognitive Functioning Predicts the Athletic Performance in Ultra-Marathon Runners. *PLOS ONE*, *10*(7), e0132943. https://doi.org/10.1371/journal.pone.0132943

Connolly, C., & Janelle, C. (2003). Attentional Strategies in Rowing: Performance, Perceived Exertion, and Gender Considerations. *Journal of Applied Sport Psychology, 15*(3), 195-212. https://doi.org/10.1080/10413200305387

Corbett, J. (2009). An Analysis of the Pacing Strategies Adopted by Elite Athletes During Track Cycling. *International Journal of Sports Physiology and Performance*, *4*(2), 195-205. https://doi.org/10.1123/IJSPP.4.2.195

Craig, N. P., & Norton, K. I. (2001). Characteristics of Track Cycling. *Sports Medicine, 31*(7), 457-468. https://doi.org/10.2165/00007256-200131070-00001

Crews, D. J. (1992). Psychological State and Running Economy. *Medicine & Science in Sports & Exercise, 24*(4), 475-482. https://doi.org/10.1249/00005768-199204000-00014

Dabbs, R., & Thewlis, T. (2022). *Tour de France 2022 route: stage by stage.* Cycling Weekly. https://www.cyclingweekly.com/news/tour-de-france-route

Dancey, C. P., & Reidy, J. (2017). *Statistics without maths for psychology* (pp. 632-632). London: Pearson.

Davidson, R. J. (2002). Anxiety and Affective Style: Role of Prefrontal Cortex and Amygdala. *Biological Psychiatry, 51*(1), 68–80. https://doi.org/10.1016/S0006-3223(01)01328-2

Davis, J. M., Zhao, Z., Stock, H. S., Mehl, K. A., Buggy, J., & Hand, G. A. (2003). Central Nervous System Effects of Caffeine and Adenosine on Fatigue. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 284*(2), R399-R404. https://doi.org/10.1152/ajpregu.00386.2002

Davranche, K., Hall, B., & McMorris, T. (2009). Effect of Acute Exercise on Cognitive Control Required During an Eriksen Flanker Task. *Journal of Sport and Exercise Psychology, 31*(5), 628-639. https://doi.org/10.1123/jsep.31.5.628

Decroix, L., Tonoli, C., Lespagnol, E., Balestra, C., Descat, A., Drittij-Reijnders, M. J., Blackwell, J. R., Stahl, W., Jones, A. M., Weseler, A. R., Bast, A., Meeusen, R., & Heyman, E. (2018). One-Week Cocoa Flavanol Intake Increases Prefrontal Cortex Oxygenation at Rest and During Moderate-Intensity Exercise in Normoxia and Hypoxia. *Journal of Applied Physiology, 125*(1), 8-18. https://doi.org/10.1152/japplphysiol.00055.2018

Decroix, L., Tonoli, C., Soares, D. D., Tagougui, S., Heyman, E., & Meeusen, R. (2016). Acute Cocoa Flavanol Improves Cerebral Oxygenation Without Enhancing Executive Function at Rest or After Exercise. *Applied Physiology, Nutrition, and Metabolism, 41*(12), 1225-1232. https://doi.org/10.1139/apnm-2016-0245

de Koning, J. J., Bobbert, M. F., & Foster, C. (1999). Determination of Optimal Pacing Strategy in Track Cycling With an Energy Flow Model. *Journal of Science and Medicine in Sport, 2*(3), 266-277. https://doi.org/10.1016/s1440-2440(99)80178-9

de Lima-Junior, D., de Sousa Fortes, L., Batista, G. R., & Vasconcelos, G. C. (2021). Letter to the Editor Regarding the Article "A 4-Week Endurance Training Program Improves Tolerance to Mental Exertion in Untrained Individuals". *Journal of Science and Medicine in Sport, 24*(12), 1200-1201. https://doi.org/10.1016/j.jsams.2021.05.001

De Luca, C. R., Wood, S. J., Anderson, V., Buchanan, J.-A., Proffitt, T. M., Mahony, K., & Pantelis, C. (2003). Normative Data From the Cantab. I: Development of

Executive Function Over the Lifespan. *Journal of Clinical and Experimental Neuropsychology, 25*(2), 242-254. https://doi.org/10.1076/jcen.25.2.242.13639

De Wachter, J., Proost, M., Habay, J., Verstraelen, M., Díaz-García, J., Hurst, P., Meeusen, R., Van Cutsem, J., & Roelands, B. (2021). Prefrontal Cortex Oxygenation During Endurance Performance: A Systematic Review of Functional Near-Infrared Spectroscopy Studies. *Frontiers in Physiology, 12*. https://doi.org/10.3389/fphys.2021.761232

Dietrich, A., & Audiffren, M. (2011). The Reticular-Activating Hypofrontality (RAH) Model of Acute Exercise. *Neuroscience & Biobehavioral Reviews, 35*(6), 1305-1325. https://doi.org/10.1016/j.neubiorev.2011.02.001

Dietrich, A., & Sparling, P. B. (2004). Endurance Exercise Selectively Impairs Prefrontal-Dependent Cognition. *Brain and Cognition, 55*(3), 516-524. https://doi.org/10.1016/j.bandc.2004.03.002

Dosenbach, N. U. F., Visscher, K. M., Palmer, E. D., Miezin, F. M., Wenger, K. K., Kang, H. C., Burgund, E. D., Grimes, A. L., Schlaggar, B. L., & Petersen, S. E. (2006). A Core System for the Implementation of Task Sets. *Neuron, 50*(5), 799-812. https://doi.org/10.1016/j.neuron.2006.04.031

Dreisbach, G., & Haider, H. (2009). How Task Representations Guide Attention: Further Evidence for the Shielding Function of Task Sets. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(2), 477-486. https://doi.org/10.1037/a0014647

Dukalski, R., Lukosch, S., Schwab, A., Beek, P. J., & Brazier, F. M. (2020). Exploring the Effect of Pacing Plan Feedback for Professional Road Cycling. The 13th Conference of the International Sports Engineering Association https://doi.org/10.3390/proceedings2020049058

Duncan, A., Meek, J. H., Clemence, M., Elwell, C. E., Fallon, P., Tyszczuk, L., Cope, M., & Delpy, D. T. (1996). Measurement of Cranial Optical Path Length as a Function of Age Using Phase Resolved Near Infrared Spectroscopy. *Pediatric Research, 39*(5), 889-894. https://doi.org/10.1203/00006450-199605000-00025

Durantin, G., Dehais, F., & Delorme, A. (2015). Characterization of Mind Wandering Using fNIRS. *Frontiers in Systems Neuroscience, 9*. https://doi.org/10.3389/fnsys.2015.00045

Eastwood, J. D., Frischen, A., Fenske, M. J., & Smilek, D. (2012). The Unengaged Mind: Defining Boredom in Terms of Attention. *Perspectives on Psychological Science*, *7*(5), 482-495. https://doi.org/10.1177/1745691612456044

Eccles, D. W., & Arsal, G. (2017). The Think Aloud Method: What is it and how do I use it? *Qualitative Research in Sport, Exercise and Health*, *9*(4), 514–531. https://doi.org/10.1080/2159676X.2017.1331501

Edwards, A. M., & Polman, R. C. J. (2013). Pacing and Awareness: Brain Regulation of Physical Activity. *Sports Medicine, 43*(11), 1057-1064. https://doi.org/10.1007/s40279-013-0091-4

Ekkekakis, P. (2005). The study of affective responses to acute exercise: The dual-mode model. In R. Stelter, K. K. Roessler, (Eds), *New approaches to sport and exercise psychology* (pp. 119-46). Oxford: Meyer & Meyer.

Ekkekakis, P. (2009). Illuminating the Black Box: Investigating Prefrontal Cortical Hemodynamics During Exercise With Near-Infrared Spectroscopy. *Journal of Sport and Exercise Psychology, 31*(4), 505-553. https://doi.org/10.1123/jsep.31.4.505

Ekkekakis, P., Parfitt, G., & Petruzzello, S. J. (2011). The Pleasure and Displeasure People Feel When They Exercise at Different Intensities: Decennial Update and Progress Towards a Tripartite Rationale for Exercise Intensity Prescription. *Sports Medicine, 41*(8), 641-671. https://doi.org/10.2165/11590680-000000000-00000

Elferink-Gemser, M. T., & Hettinga, F. J. (2017). Pacing and Self-regulation: Important Skills for Talent Development in Endurance Sports. *International Journal of Sports Physiology and Performance, 12*(6), 831–835. https://doi.org/10.1123/IJSPP.2017-0080

Englert, C., Dziuba, A., Giboin, L. S., & Wolff, W. (2021). Elites do not Deplete - No Effect of Prior Mental Exertion on Subsequent Shooting Performance in

Elite Shooters. *Frontiers in Psychology, 12*. https://doi.org/10.3389/fpsyg.2021.668108

Englert, C., Dziuba, A., Wolff, W., & Giboin, L. S. (2021). An Investigation of the Effects of Self-Reported Self-Control Strength on Shooting Performance. *Psychology of Sport and Exercise, 52*, 101839. https://doi.org/10.1016/j.psychsport.2020.101839

Erickson, K. I., & Kramer, A. F. (2008). Aerobic Exercise Effects on Cognitive and Neural Plasticity in Older Adults. *British Journal of Sports Medicine, 43*(1), 22-24. https://doi.org/10.1136/bjsm.2008.052498

Ericsson, K. A., & Simon, H. A. (1980). Verbal Reports as Data. *Psychological Review, 87*(3), 215-251. https://doi.org/10.1037/0033-295x.87.3.215

Ettema, G., & Lorås, H. W. (2009). Efficiency in Cycling: A Review. *European Journal of Applied Physiology, 106*(1), 1-14. https://doi.org/10.1007/s00421-009-1008-7

Evans, D. R., Boggero, I. A., & Segerstrom, S. C. (2016). The Nature of Self-Regulatory Fatigue and “Ego Depletion”: Lessons From Physical Fatigue. *Personality and Social Psychology Review*, *20*(4), 291-310. https://doi.org/10.1177/1088868315597841

Fan, J. L., Bourdillon, N., & Kayser, B. (2013). Effect of End-Tidal CO_2 Clamping on Cerebrovascular Function, Oxygenation, and Performance During 15-km Time Trial Cycling in Severe Normobaric Hypoxia: The Role of Cerebral O_2 Delivery. *Physiological Reports*, *1*(3), 1-15. https://doi.org/10.1002/phy2.66

Fan, J. L., Bourdillon, N., Meyer, P., & Kayser, B. (2018). Oral Nitrate Supplementation Differentially Modulates Cerebral Artery Blood Velocity and Prefrontal Tissue Oxygenation During 15-km Time-Trial Cycling in Normoxia but not in Hypoxia. *Frontiers in Physiology, 9*. https://doi.org/10.3389/fphys.2018.00869

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A Flexible Statistical Power Analysis Program for the Social, Behavioral, and Biomedical Sciences. *Behavior Research Methods, 39*(2), 175-191.

https://doi.org/10.3758/BF03193146

Faulkner, J., Lambrick, D., Kaufmann, S., & Stoner, L. (2016). Effects of Upright and Recumbent Cycling on Executive Function and Prefrontal Cortex Oxygenation in Young Healthy Men. *Journal of Physical Activity and Health, 13*(8), 882-887. https://doi.org/10.1123/jpah.2015-0454

Fekete, T., Rubin, D., Carlson, J. M., & Mujica-Parodi, L. R. (2011). A Stand-Alone Method for Anatomical Localization of NIRS Measurements. *NeuroImage, 56*(4), 2080-2088. https://doi.org/10.1016/j.neuroimage.2011.03.068

Ferguson, S. A. H., Eves, N. D., Roy, B. D., Hodges, G. J., & Cheung, S. S. (2018). Effects of Mild Whole Body Hypothermia on Self-Paced Exercise Performance. *Journal of Applied Physiology, 125*(2), 479-485. https://doi.org/10.1152/japplphysiol.01134.2017

Ferrari, M., & Quaresima, V. (2012). A Brief Review on the History of Human Functional Near-Infrared Spectroscopy (fNIRS) Development and Fields of Application. *NeuroImage*, *63*(2), 921-935. https://doi.org/10.1016/J.NEUROIMAGE.2012.03.049

Field, A. (2013). *Discovering statistics using IBM SPSS statistics*. London, UK: SAGE Publications Ltd.

Filipas, L., Bonato, M., Gallo, G., & Codella, R. (2022). Effects of 16 Weeks of Pyramidal and Polarized Training Intensity Distributions in Well-Trained Endurance Runners. *Scandinavian Journal of Medicine & Science in Sports, 32*(3), 498-511. https://doi.org/10.1111/SMS.14101

Filipas, L., Martin, K., Northey, J. M., La Torre, A., Keegan, R., & Rattray, B. (2020). A 4-Week Endurance Training Program Improves Tolerance to Mental Exertion in Untrained Individuals. *Journal of Science and Medicine in Sport, 23*(12), 1215-1219. https://doi.org/10.1016/j.jsams.2020.04.020

Filosa, J. A., & Blanco, V. M. (2007). Neurovascular Coupling in the Mammalian Brain: Neuronal-Glial-Vascular Communication. *Experimental Physiology, 92*(4), 641-646. https://doi.org/10.1113/expphysiol.2006.036368

Foster, C., Schrager, M., Snyder, A. C., & Thompson, N. N. (1994). Pacing Strategy and Athletic Performance. *Sports Medicine, 17*(2), 77-85. https://doi.org/10.2165/00007256-199417020-00001

Fox, M. C., Ericsson, K. A., & Best, R. (2011). Do Procedures for Verbal Reporting of Thinking Have to be Reactive? A Meta-Analysis and Recommendations for Best Reporting Methods. *Psychological Bulletin*, *137*(2), 316-344. https://doi.org/10.1037/a0021663

Freud, S. (1900). The interpretation of dreams. In J. Stracey (Ed.), *The standard edition of the complete psychological works of Sigmund Freud, vols. 4–5*. London: Hogart

Friedman, N. P., Miyake, A., Young, S. E., DeFries, J. C., Corley, R. P., & Hewitt, J. K. (2008). Individual Differences in Executive Functions are Almost Entirely Genetic in Origin. *Journal of Experimental Psychology: General, 137*(2), 201-225. https://doi.org/10.1037/0096-3445.137.2.201

Funahashi, S., & Andreau, J. M. (2013). Prefrontal Cortex and Neural Mechanisms of Executive Function. *Journal of Physiology-Paris*, *107*(6), 471-482. https://doi.org/10.1016/j.jphysparis.2013.05.001

Furley, P., & Wood, G. (2016). Working Memory, Attentional Control, and Expertise in Sports: A Review of Current Literature and Directions for Future Research. *Journal of Applied Research in Memory and Cognition*, *5*(4), 415-425. https://doi.org/10.1016/j.jarmac.2016.05.001

Gandevia, S. C. (2001). Spinal and Supraspinal Factors in Human Muscle Fatigue. *Physiological Reviews, 81*(4), 1725-1789. https://doi.org/10.1152/physrev.2001.81.4.1725

Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I.-M., Nieman, D. C., & Swain, D. P. (2011). Quantity and Quality of Exercise for Developing and Maintaining Cardiorespiratory, Musculoskeletal, and Neuromotor Fitness in Apparently Healthy Adults: Guidance for Prescribing Exercise. *Medicine & Science in Sports & Exercise, 43*(7), 1334-1359. https://doi.org/10.1249/mss.0b013e318213fefb

Giambra, L. M. (1995). A Laboratory Method for Investigating Influences on

Switching Attention to Task-Unrelated Imagery and Thought. *Consciousness and Cognition*, *4*(1), 1-21. https://doi.org/10.1006/CCOG.1995.1001

Giles, G. E., Cantelon, J. A., Eddy, M. D., Brunyé, T. T., Urry, H. L., Taylor, H. A., Mahoney, C. R., & Kanarek, R. B. (2018). Cognitive Reappraisal Reduces Perceived Exertion During Endurance Exercise. *Motivation and Emotion, 42*(4), 482-496. https://doi.org/10.1007/s11031-018-9697-z

Goldberg, L., Elliot, D. L., & Kuehl, K. S. (1988). Assessment of Exercise Intensity Formulas by use of Ventilatory Threshold. *Chest, 94*(1), 95-98. https://doi.org/10.1378/chest.94.1.95

Goschke, T. (2003). Voluntary action and cognitive control from a cognitive neuroscience perspective. In S. Maasen, W. Prinz, & G. Roth (Eds.), *Voluntary action: Brains, minds, and sociality* (pp. 49–85). Oxford: University Press.

Graham, J. D., Martin Ginis, K. A., & Bray, S. R. (2017). Exertion of Self-Control Increases Fatigue, Reduces Task Self-Efficacy, and Impairs Performance of Resistance Exercise. *Sport, Exercise, and Performance Psychology, 6*(1), 70-88. https://doi.org/10.1037/spy0000074

Gross, J. J. (1998). The Emerging Field of Emotion Regulation: An Integrative Review. *Review of General Psychology, 2*(3), 271-299. https://doi.org/10.1037/1089-2680.2.3.27

Haberman, J., & Whitney, D. (2011). Ensemble perception: Summarizing the scene and broadening the limits of visual processing. In J., Wolfe, & L., Robertson (Eds.), *From perception to consciousness: Searching with Anne Treisman* (pp. 1–21). Oxford: University Press.

Halperin, I., & Emanuel, A. (2020). Rating of Perceived Effort: Methodological Concerns and Future Directions. *Sports Medicine, 50*(4), 679-687. https://doi.org/10.1007/s40279-019-01229-z

Hamlin, M. J., Marshall, H. C., Hellemans, J., & Ainslie, P. N. (2010). Effect of Intermittent Hypoxia on Muscle and Cerebral Oxygenation During a 20-km Time Trial in Elite Athletes: A Preliminary Report. *Applied Physiology, Nutrition, and Metabolism, 35*(4), 548-559. https://doi.org/10.1139/h10-044

Hanley, B. (2014). Senior Men’s Pacing Profiles at the IAAF World Cross Country Championships. *Journal of Sports Sciences*, *32*(11), 1060-1065. https://doi.org/10.1080/02640414.2013.878807

Hanley, B. (2015). Pacing Profiles and Pack Running at the IAAF World Half Marathon Championships. *Journal of Sports Sciences*, *33*(11), 1189-1195. https://doi.org/10.1080/02640414.2014.988742

Hardy, C. J., & Rejeski, W. J. (1989). Not What, but How One Feels: The Measurement of Affect During Exercise. *Journal of Sport and Exercise Psychology, 11*(3), 304-317. https://doi.org/10.1123/jsep.11.3.304

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. *Advances in Psychology*, 139-183. https://doi.org/10.1016/s0166-4115(08)62386-9

Hatfield, B. D., Haufler, A. J., Hung, T.-M., & Spalding, T. W. (2004). Electroencephalographic Studies of Skilled Psychomotor Performance. *Journal of Clinical Neurophysiology, 21*(3), 144-156. https://doi.org/10.1097/00004691-200405000-00003

Hatzigeorgiadis, A., & Galanis, E. (2017). Self-Talk Effectiveness and Attention. *Current Opinion in Psychology*, *16*, 138–142. https://doi.org/10.1016/J.COPSYC.2017.05.014

Heil, M., Osman, A., Wiegelmann, J., Rolke, B., & Hennighausen, E. (2000). N200 in the Eriksen-Task: Inhibitory Executive Processes? *Journal of Psychophysiology, 14*(4), 218-225. https://doi.org/10.1027//0269-8803.14.4.218

Herold, F., Wiegel, P., Scholkmann, F., & Müller, N. (2018). Applications of Functional Near-Infrared Spectroscopy (fNIRS) Neuroimaging in Exercise-Cognition Science: A Systematic, Methodology-Focused Review. *Journal of Clinical Medicine, 7*(12), 466. https://doi.org/10.3390/jcm7120466

Hettinga, F. J., de Koning, J. J., Hulleman, M., & Foster, C. (2012). Relative Importance of Pacing Strategy and Mean Power Output in 1500-m Self-Paced Cycling. *British Journal of Sports Medicine*, *46*(1), 30-35. https://doi.org/10.1136/bjsm.2009.064261

Hill, A. V., & Lupton, H. (1923). Muscular Exercise, Lactic Acid, and the Supply and Utilization of Oxygen. *QJM, os-16*(62), 135-171. https://doi.org/10.1093/qjmed/os-16.62.135

Hill, D. M., Hanton, S., Matthews, N., & Fleming, S. (2010). Choking in Sport: A Review. *International Review of Sport and Exercise Psychology, 3*(1), 24-39. https://doi.org/10.1080/17509840903301199

Historical chart of number of parkrun events, parkrunners and volunteers. (2022). Parkrun. https://www.parkrun.org.uk/results/historicalchart/

Hofmann, W., Friese, M., & Roefs, A. (2009). Three Ways to Resist Temptation: The Independent Contributions of Executive Attention, Inhibitory Control, and Affect Regulation to the Impulse Control of Eating Behavior. *Journal of Experimental Social Psychology*, *45*(2), 431–435. https://doi.org/10.1016/j.jesp.2008.09.013

Hofmann, W., Schmeichel, B. J., & Baddeley, A. D. (2012). Executive Functions and Self-Regulation. *Trends in Cognitive Sciences*, *16*(3), 174–180. https://doi.org/10.1016/j.tics.2012.01.006

Holgado, D., Zandonai, T., Ciria, L. F., Zabala, M., Hopker, J., & Sanabria, D. (2019). Transcranial Direct Current Stimulation (tDCS) Over the Left Prefrontal Cortex Does Not Affect Time-Trial Self-Paced Cycling Performance: Evidence From Oscillatory Brain Activity and Power Output. *PLOS ONE*, *14*(2), e0210873. https://doi.org/10.1371/JOURNAL.PONE.0210873

Holroyd, C. B. (2016). The waste disposal problem of effortful control. In T. S. Braver (Ed.), *Motivation and cognitive control* (pp. 235–260). Routledge/Taylor & Francis Group.

Hunte, R., Cooper, S. B., Taylor, I. M., Nevill, M. E., & Boat, R. (2021). The Mechanisms Underpinning the Effects of Self-Control Exertion on Subsequent Physical Performance: A Meta-Analysis. *International Review of Sport and Exercise Psychology,* 1-28. https://doi.org/10.1080/1750984x.2021.2004610

Huppert, T. J. (2016). Commentary on the Statistical Properties of Noise and Its Implication on General Linear Models in Functional Near-Infrared

Spectroscopy. *Neurophotonics, 3*(1), 010401. https://doi.org/10.1117/1.nph.3.1.010401

Hutchinson, J. C., & Tenenbaum, G. (2007). Attention Focus During Physical Effort: The Mediating Role of Task Intensity. *Psychology of Sport and Exercise*, *8*(2), 233–245. https://doi.org/10.1016/j.psychsport.2006.03.006

Hyland-Monks, R., Cronin, L., McNaughton, L., & Marchant, D. (2018). The Role of Executive Function in the Self-Regulation of Endurance Performance: A Critical Review. *Progress in Brain Research, 240*, 353-370. https://doi.org/10.1016/bs.pbr.2018.09.011

Hyland-Monks, R., Marchant, D., & Cronin, L. (2022). Self-Paced Endurance Performance and Cerebral Hemodynamics of the Prefrontal Cortex: A Scoping Review of Methodology and Findings. *Perceptual and Motor Skills, 129*(4), 1089-1114. https://doi.org/10.1177/00315125221101017

Inzlicht, M., & Marcora, S. M. (2016). The Central Governor Model of Exercise Regulation Teaches Us Precious Little About the Nature of Mental Fatigue and Self-Control Failure. *Frontiers in Psychology, 7*. https://doi.org/10.3389/fpsyg.2016.00656

Jackson, S. A. (1995). Factors Influencing the Occurrence of Flow State in Elite Athletes. *Journal of Applied Sport Psychology*, *7*(2), 138-166. https://doi.org/10.1080/10413209508406962

Jacobson, J., & Matthaeus, L. (2014). Athletics and Executive Functioning: How Athletic Participation and Sport Type Correlate With Cognitive Performance. *Psychology of Sport and Exercise, 15*(5), 521-527. https://doi.org/10.1016/j.psychsport.2014.05.005

Jones, H. S., Williams, E. L., Bridge, C. A., Marchant, D., Midgley, A. W., Micklewright, D., & Mc Naughton, L. R. (2013). Physiological and Psychological Effects of Deception on Pacing Strategy and Performance: A Review. *Sports Medicine*, *43*(12), 1243-1257. https://doi.org/10.1007/s40279-013-0094-1

Journal Article Reporting Standards (JARS). (2022). American Psychological

Association (APA). https://apastyle.apa.org/jars/mixed-methods

Joyner, M. J., & Coyle, E. F. (2008). Endurance Exercise Performance: The Physiology of Champions: Factors That Make Champions. *The Journal of Physiology, 586*(1), 35-44. https://doi.org/10.1113/jphysiol.2007.143834

Kalén, A., Bisagno, E., Musculus, L., Raab, M., Pérez-Ferreirós, A., Williams, A. M., Araújo, D., Lindwall, M., & Ivarsson, A. (2021). The Role of Domain-Specific and Domain-General Cognitive Functions and Skills in Sports Performance: A Meta-Analysis. *Psychological Bulletin, 147*(12), 1290-1308. https://doi.org/10.1037/bul0000355

Kamijo, K., Hayashi, Y., Sakai, T., Yahiro, T., Tanaka, K., & Nishihira, Y. (2009). Acute Effects of Aerobic Exercise on Cognitive Function in Older Adults. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 64B*(3), 356-363. https://doi.org/10.1093/geronb/gbp030

Karsdorp, P. A., Geenen, R., & Vlaeyen, J. W. S. (2014). Response Inhibition Predicts Painful Task Duration and Performance in Healthy Individuals Performing a Cold Pressor Task in a Motivational Context: Response Inhibition and Pain. *European Journal of Pain, 18*(1), 92-100. https://doi.org/10.1002/j.1532-2149.2013.00348.x

Key figures. (n.d.). L'Etape du Tour de France. https://www.letapedutourdefrance.com/en/event/key-figures

Krenn, B., Finkenzeller, T., Würth, S., & Amesberger, G. (2018). Sport Type Determines Differences in Executive Functions in Elite Athletes. *Psychology of Sport and Exercise, 38*, 72-79. https://doi.org/10.1016/j.psychsport.2018.06.002

Kurzban, R. (2010). Does the Brain Consume Additional Glucose During Self-Control Tasks? *Evolutionary Psychology, 8*(2), 147470491000800. https://doi.org/10.1177/147470491000800208

Lakens, D. (2013). Calculating and Reporting Effect Sizes to Facilitate Cumulative Science: A Practical Primer for T-Tests and ANOVAs. *Frontiers in Psychology, 4*. https://doi.org/10.3389/fpsyg.2013.00863

Lamport, D. J., Pal, D., Moutsiana, C., Field, D. T., Williams, C. M., Spencer, J. P.

E., & Butler, L. T. (2015). The Effect of Flavanol-Rich Cocoa on Cerebral Perfusion in Healthy Older Adults During Conscious Resting State: A Placebo Controlled, Crossover, Acute Trial. *Psychopharmacology*, *232*(17), 3227-3234. https://doi.org/10.1007/S00213-015-3972-4/TABLES/2

Lane, A. M., Beedie, C. J., Jones, M. V., Uphill, M., & Devonport, T. J. (2012). The BASES Expert Statement on Emotion Regulation in Sport. *Journal of Sports Sciences*, *30*(11), 1189-1195. https://doi.org/10.1080/02640414.2012.693621

Latinjak, A. T. (2018). Athletes' Self-Reports on Mind Wandering While Practicing Sports: An Exploratory Two-Study Project. *Journal of Clinical Sport Psychology*, *12*(3), 432-447. https://doi.org/10.1123/JCSP.2017-0023

Lattari, E., de Oliveira, B. S., Oliveira, B. R. R., de Mello Pedreiro, R. C., Machado, S., & Neto, G. A. M. (2018). Effects of Transcranial Direct Current Stimulation on Time Limit and Ratings of Perceived Exertion in Physically Active Women. *Neuroscience Letters*, *662*, 12–16. https://doi.org/10.1016/J.NEULET.2017.10.007

Lee, J. S., Keil, M., & Wong, K. F. E. (2015). The Effect of Goal Difficulty on Escalation of Commitment: The Effect of Goal Difficulty on Escalation. *Journal of Behavioral Decision Making, 28*(2), 114-129. https://doi.org/10.1002/bdm.1835

Liao, Y.-H., Mündel, T., Yang, Y.-T., Wei, C.-C., & Tsai, S.-C. (2019). Effects of Periodic Carbohydrate Ingestion on Endurance and Cognitive Performances During a 40-km Cycling Time-Trial Under Normobaric Hypoxia in Well-Trained Triathletes. *Journal of Sports Sciences, 37*(16), 1805-1815. https://doi.org/10.1080/02640414.2019.1595338

Lindner, C., Lindner, M. A., & Retelsdorf, J. (2019). Measuring Self-Control Depletion in Achievement Situations: A Validation of the 5-Item Brief State Self-Control Capacity Scale. *Diagnostica, 65*(4), 228–242. https://doi.org/10.1026/0012-1924/a000230

Lipscomb, M. (2012). Abductive Reasoning and Qualitative Research: Abductive Reasoning. *Nursing Philosophy, 13*(4), 244-256. https://doi.org/10.1111/j.1466-769x.2011.00532.x

Lovatt, D., Xu, Q., Liu, W., Takano, T., Smith, N. A., Schnermann, J., Tieu, K., & Nedergaard, M. (2012). Neuronal Adenosine Release, and Not Astrocytic ATP Release, Mediates Feedback Inhibition of Excitatory Activity. *Proceedings of the National Academy of Sciences, 109*(16), 6265-6270. https://doi.org/10.1073/pnas.1120997109

Lucía, A., Pardo, J., Durántez, A., Hoyos, J., & Chicharro, J. (1998). Physiological Differences Between Professional and Elite Road Cyclists. *International Journal of Sports Medicine, 19*(05), 342-348. https://doi.org/10.1055/s-2007-971928

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the Role of the Dorsolateral Prefrontal and Anterior Cingulate Cortex in Cognitive Control. *Science, 288*(5472), 1835-1838. https://doi.org/10.1126/science.288.5472.1835

Machado, S., Jansen, P., Almeida, V., & Veldema, J. (2019). Is tDCS an Adjunct Ergogenic Resource for Improving Muscular Strength and Endurance Performance? A Systematic Review. *Frontiers in Psychology, 10*. https://doi.org/10.3389/fpsyg.2019.01127

MacMahon, C., Schücker, L., Hagemann, N., & Strauss, B. (2014). Cognitive Fatigue Effects on Physical Performance During Running. *Journal of Sport and Exercise Psychology, 36*(4), 375-381. https://doi.org/10.1123/jsep.2013-0249

Marcora, S. (2009). Last Word on Viewpoint: Perception of Effort During Exercise is Independent of Afferent Feedback From Skeletal Muscles, Heart, and Lungs. *Journal of Applied Physiology*, *106*(6), 2067–2067. https://doi.org/10.1152/japplphysiol.90989.2008

Marcora, S. (2010). Counterpoint: Afferent Feedback From Fatigued Locomotor Muscles is Not an Important Determinant of Endurance Exercise Performance. *Journal of Applied Physiology, 108*(2), 454-456. https://doi.org/10.1152/japplphysiol.00976.2009a

Marcora, S. M., Staiano, W., & Merlini, M. (2015). A Randomized Controlled Trial of Brain Endurance Training (BET) to Reduce Fatigue During Endurance Exercise: 754 Board #150 May 27, 3 30 PM - 5 00 PM. *Medicine & Science in*

Sports & Exercise, *47*(5S), 198. https://doi.org/10.1249/01.mss.0000476967.03579.44

Martin, J. J., Craib, M., & Mitchell, V. (1995). The Relationships of Anxiety and Self-Attention to Running Economy in Competitive Male Distance Runners. *Journal of Sports Sciences*, *13*(5), 371-376. https://doi.org/10.1080/02640419508732252

Martin, K., Staiano, W., Menaspà, P., Hennessey, T., Marcora, S., Keegan, R., Thompson, K. G., Martin, D., Halson, S., & Rattray, B. (2016). Superior Inhibitory Control and Resistance to Mental Fatigue in Professional Road Cyclists. *PLOS ONE*, *11*(7), e0159907. https://doi.org/10.1371/journal.pone.0159907

Massey, H. S., Whitehead, A. E., Marchant, D., Polman, R. C., & Williams, E. L. (2020). An Investigation of Expertise in Cycling: Eye Tracking, Think Aloud and the Influence of a Competitor. *Psychology of Sport and Exercise*, *49*, 101681. https://doi.org/10.1016/j.psychsport.2020.101681

Maxwell, S. E., Lau, M. Y., & Howard, G. S. (2015). Is Psychology Suffering From a Replication Crisis? What Does "Failure to Replicate" Really Mean? *American Psychologist*, *70*(6), 487-498. https://doi.org/10.1037/a0039400

Mayberg, H. S., Lozano, A. M., Voon, V., McNeely, H. E., Seminowicz, D., Hamani, C., Schwalb, J. M., & Kennedy, S. H. (2005). Deep Brain Stimulation for Treatment-Resistant Depression. *Neuron*, *45*(5), 651-660. https://doi.org/10.1016/j.neuron.2005.02.014

McAlister, A., Lee, D., Ehlert, K., Kajfez, R., Faber, C., & Kennedy, M. (2017). Qualitative Coding: An Approach to Assess Inter-Rater Reliability. 2017 ASEE Annual Conference & Exposition Proceedings https://doi.org/10.18260/1-2--28777

McAuley, E., Duncan, T., & Tammen, V. V. (1989). Psychometric Properties of the Intrinsic Motivation Inventory in a Competitive Sport Setting: A Confirmatory Factor Analysis. *Research Quarterly for Exercise and Sport*, *60*(1), 48-58. https://doi.org/10.1080/02701367.1989.10607413

McCormick, A., Meijen, C., Anstiss, P. A., & Jones, H. S. (2019). Self-Regulation in Endurance Sports: Theory, Research, and Practice. *International Review of Sport and Exercise Psychology, 12*(1), 235-264. https://doi.org/10.1080/1750984x.2018.1469161

McCormick, A., Meijen, C., & Marcora, S. (2015). Psychological Determinants of Whole-Body Endurance Performance. *Sports Medicine, 45*(7), 997-1015. https://doi.org/10.1007/s40279-015-0319-6

Meijen, C., McCormick, A., Anstiss, P. A., & Marcora, S. M. (2022). "Short and Sweet": A Randomized Controlled Initial Investigation of Brief Online Psychological Interventions With Endurance Athletes. *The Sport Psychologist, 36*(1), 20-28. https://doi.org/10.1123/tsp.2020-0088

Micklewright, D., Angus, C., Suddaby, J., St. Clair Gibson, A., Sandercock, G., & Chinnasamy, C. (2012). Pacing Strategy in Schoolchildren Differs With Age and Cognitive Development. *Medicine & Science in Sports & Exercise, 44*(2), 362-369. https://doi.org/10.1249/mss.0b013e31822cc9ec

Micklewright, D., Kegerreis, S., Raglin, J., & Hettinga, F. (2017). Will the Conscious–Subconscious Pacing Quagmire Help Elucidate the Mechanisms of Self-Paced Exercise? New Opportunities in Dual Process Theory and Process Tracing Methods. *Sports Medicine, 47*(7), 1231-1239. https://doi.org/10.1007/s40279-016-0642-6

Micklewright, D., Papadopoulou, E., Swart, J., & Noakes, T. (2010). Previous Experience Influences Pacing During 20 km Time Trial Cycling. *British Journal of Sports Medicine, 44*(13), 952-960. https://doi.org/10.1136/bjsm.2009.057315

Micklewright, D., St. Clair Gibson, A., Gladwell, V., & Al Salman, A. (2017). Development and Validity of the Rating-of-Fatigue Scale. *Sports Medicine, 47*(11), 2375-2393. https://doi.org/10.1007/s40279-017-0711-5

Miles, M. B., & Huberman, A. (1994). *An expanded sourcebook: Qualitative data analysis* (2nd Edition). Sage Publications.

Miller, E. K., & Cohen, J. D. (2001). An Integrative Theory of Prefrontal Cortex

Function. *Annual Review of Neuroscience, 24*(1), 167-202. https://doi.org/10.1146/annurev.neuro.24.1.167

Miś, M., & Kowalczyk, M. (2021). Mind-Wandering During Long-Distance Running and Mood Change. The Role of Working Memory Capacity and Temporal Orientation of Thoughts. *International Journal of Sport and Exercise Psychology, 19*(5), 815-833. https://doi.org/10.1080/1612197x.2020.1766538

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The Unity and Diversity of Executive Functions and Their Contributions to Complex “Frontal Lobe” Tasks: A Latent Variable Analysis. *Cognitive Psychology*, *41*(1), 49-100. https://doi.org/10.1006/cogp.1999.0734

Modi, H. N., Singh, H., Yang, G.-Z., Darzi, A., & Leff, D. R. (2017). A Decade of Imaging Surgeons' Brain Function (Part I): Terminology, Techniques, and Clinical Translation. *Surgery, 162*(5), 1121-1130. https://doi.org/10.1016/j.surg.2017.05.021

Morree, H. M., Klein, C., & Marcora, S. M. (2012). Perception of Effort Reflects Central Motor Command During Movement Execution: Neurophysiology of Perceived Effort. *Psychophysiology, 49*(9), 1242-1253. https://doi.org/10.1111/j.1469-8986.2012.01399.x

Muraven, M., Baumeister, R. F., & Tice, D. M. (1999). Longitudinal Improvement of Self-Regulation Through Practice: Building Self-Control Strength Through Repeated Exercise. *The Journal of Social Psychology*, *139*(4), 446-457. https://doi.org/10.1080/00224549909598404

Myers, J., Atwood, J. E., Sullivan, M., Forbes, S., Friis, R., Pewen, W., & Froelicher, V. (1987). Perceived Exertion and Gas Exchange After Calcium and Beta-Blockade in Atrial Fibrillation. *Journal of Applied Physiology, 63*(1), 97-104. https://doi.org/10.1152/jappl.1987.63.1.97

Neumann, D. L., Moffitt, R. L., Thomas, P. R., Loveday, K., Watling, D. P., Lombard, C. L., Antonova, S., & Tremeer, M. A. (2018). A Systematic Review of the Application of Interactive Virtual Reality to Sport. *Virtual Reality*, *22*(3), 183-198. https://doi.org/10.1007/s10055-017-0320-5

Nicholls, A. R., Polman, R. C. J., Levy, A. R., & Backhouse, S. H. (2008). Mental Toughness, Optimism, Pessimism, and Coping Among Athletes. *Personality and Individual Differences, 44*(5), 1182-1192. https://doi.org/10.1016/j.paid.2007.11.011

Nielsen, H. B., Boushel, R., Madsen, P., & Secher, N. H. (1999). Cerebral Desaturation During Exercise Reversed by O_2 Supplementation. *American Journal of Physiology-Heart and Circulatory Physiology, 277*(3), H1045-H1052. https://doi.org/10.1152/ajpheart.1999.277.3.h1045

Nitsche, M. A., & Paulus, W. (2000). Excitability Changes Induced in the Human Motor Cortex by Weak Transcranial Direct Current Stimulation. *The Journal of Physiology, 527*(3), 633-639. https://doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x

Noakes, T. D. (2004). From Catastrophe to Complexity: A Novel Model of Integrative Central Neural Regulation of Effort and Fatigue During Exercise in Humans. *British Journal of Sports Medicine, 38*(4), 511-514. https://doi.org/10.1136/bjsm.2003.009860

Noakes, T. D. (2008). Testing for Maximum Oxygen Consumption Has Produced a Brainless Model of Human Exercise Performance. *British Journal of Sports Medicine*, *42*(7), 551-555. https://doi.org/10.1136/bjsm.2008.046821

Noakes, T. D. (2012a). The Central Governor Model in 2012: Eight New Papers Deepen Our Understanding of the Regulation of Human Exercise Performance. *British Journal of Sports Medicine*, *46*(1), 1-3. https://doi.org/10.1136/bjsports-2011-090811

Noakes, T. D. (2012b). Fatigue is a Brain-Derived Emotion That Regulates the Exercise Behavior to Ensure the Protection of Whole Body Homeostasis. *Frontiers in Physiology, 3*. https://doi.org/10.3389/fphys.2012.00082

Nybo, L., & Nielsen, B. (2001). Perceived Exertion is Associated With an Altered Brain Activity During Exercise With Progressive Hyperthermia. *Journal of Applied Physiology, 91*(5), 2017-2023. https://doi.org/10.1152/jappl.2001.91.5.2017

O'Donnell, D. E., Banzett, R. B., Carrieri-Kohlman, V., Casaburi, R., Davenport, P. W., Gandevia, S. C., Gelb, A. F., Mahler, D. A., & Webb, K. A. (2007). Pathophysiology of Dyspnea in Chronic Obstructive Pulmonary Disease: A Roundtable. *Proceedings of the American Thoracic Society, 4*(2), 145-168. https://doi.org/10.1513/pats.200611-159cc

Orihuela-Espina, F., Leff, D. R., James, D. R. C., Darzi, A. W., & Yang, G. Z. (2010). Quality Control and Assurance in Functional Near Infrared Spectroscopy (fNIRS) Experimentation. *Physics in Medicine and Biology, 55*(13), 3701-3724. https://doi.org/10.1088/0031-9155/55/13/009

Pageaux, B., Lepers, R., Dietz, K. C., & Marcora, S. M. (2014). Response Inhibition Impairs Subsequent Self-Paced Endurance Performance. *European Journal of Applied Physiology*, *114*(5), 1095-1105. https://doi.org/10.1007/s00421-014-2838-5

Pageaux, B., Marcora, S. M., Rozand, V., & Lepers, R. (2015). Mental Fatigue Induced by Prolonged Self-Regulation Does Not Exacerbate Central Fatigue During Subsequent Whole-Body Endurance Exercise. *Frontiers in Human Neuroscience, 9*. https://doi.org/10.3389/fnhum.2015.00067

Paulus, M. P., Potterat, E. G., Taylor, M. K., Van Orden, K. F., Bauman, J., Momen, N., Padilla, G. A., & Swain, J. L. (2009). A Neuroscience Approach to Optimizing Brain Resources for Human Performance in Extreme Environments. *Neuroscience & Biobehavioral Reviews, 33*(7), 1080-1088. https://doi.org/10.1016/j.neubiorev.2009.05.003

Pauw, K. D., Roelands, B., Cheung, S. S., de Geus, B., Rietjens, G., & Meeusen, R. (2013). Guidelines to Classify Subject Groups in Sport-Science Research. *International Journal of Sports Physiology and Performance, 8*(2), 111-122. https://doi.org/10.1123/ijspp.8.2.111

Pekrun, R., Goetz, T., Daniels, L. M., Stupnisky, R. H., & Perry, R. P. (2010). Boredom in Achievement Settings: Exploring Control-Value Antecedents and Performance Outcomes of a Neglected Emotion. *Journal of Educational Psychology*, *102*(3), 531-549. https://doi.org/10.1037/A0019243

Perrey, S. (2008). Non-Invasive NIR Spectroscopy of Human Brain Function During

Exercise. *Methods, 45*(4), 289-299. https://doi.org/10.1016/j.ymeth.2008.04.005

Perrey, S., & Besson, P. (2018). Studying Brain Activity in Sports Performance: Contributions and Issues. *Progress in Brain Research*, 247-267. https://doi.org/10.1016/bs.pbr.2018.07.004

Phillips, C., Baktir, M. A., Srivatsan, M., & Salehi, A. (2014). Neuroprotective Effects of Physical Activity on the Brain: A Closer Look at Trophic Factor Signaling. *Frontiers in Cellular Neuroscience, 8*. https://doi.org/10.3389/fncel.2014.00170

Pinti, P., Scholkmann, F., Hamilton, A., Burgess, P., & Tachtsidis, I. (2019). Current Status and Issues Regarding Pre-processing of fNIRS Neuroimaging Data: An Investigation of Diverse Signal Filtering Methods Within a General Linear Model Framework. *Frontiers in Human Neuroscience, 12*. https://doi.org/10.3389/fnhum.2018.00505

Pires, F. O., dos Anjos, C. A. S., Covolan, R. J. M., Pinheiro, F. A., St. Clair Gibson, A., Noakes, T. D., Magalhães, F. H., & Ugrinowitsch, C. (2016). Cerebral Regulation in Different Maximal Aerobic Exercise Modes. *Frontiers in Physiology, 7*. https://doi.org/10.3389/fphys.2016.00253

Pontifex, M. B., & Hillman, C. H. (2007). Neuroelectric and Behavioral Indices of Interference Control During Acute Cycling. *Clinical Neurophysiology, 118*(3), 570-580. https://doi.org/10.1016/j.clinph.2006.09.029

Posadzki, P., Pieper, D., Bajpai, R., Makaruk, H., Könsgen, N., Neuhaus, A. L., & Semwal, M. (2020). Exercise/Physical Activity and Health Outcomes: An Overview of Cochrane Systematic Reviews. *BMC Public Health, 20*(1). https://doi.org/10.1186/s12889-020-09855-3

Putman, P., Antypa, N., Crysovergi, P., & van der Does, W. A. J. (2010). Exogenous Cortisol Acutely Influences Motivated Decision Making in Healthy Young Men. *Psychopharmacology, 208*(2), 257-263. https://doi.org/10.1007/s00213-009-1725-y

Radel, R., Brisswalter, J., & Perrey, S. (2017). Saving Mental Effort to Maintain Physical Effort: A Shift of Activity Within the Prefrontal Cortex in Anticipation of Prolonged Exercise. *Cognitive, Affective, & Behavioral Neuroscience, 17*(2), 305-314. https://doi.org/10.3758/s13415-016-0480-x

Record numbers once again at 2019 London Marathon. (2019). Run Britain. https://www.runbritain.com/news/record-numbers-at-2019-london-marathon

Renfree, A., & Casado, A. (2018). Athletic Races Represent Complex Systems, and Pacing Behavior Should Be Viewed as an Emergent Phenomenon. *Frontiers in Physiology, 9*. https://doi.org/10.3389/fphys.2018.01432

Renfree, A., Crivoi do Carmo, E., & Martin, L. (2016). The Influence of Performance Level, Age and Gender on Pacing Strategy During a 100-km Ultramarathon. *European Journal of Sport Science, 16*(4), 409-415. https://doi.org/10.1080/17461391.2015.1041061

Renfree, A., Martin, L., Micklewright, D., & St. Clair Gibson, A. (2014). Application of Decision-Making Theory to the Regulation of Muscular Work Rate during Self-Paced Competitive Endurance Activity. *Sports Medicine, 44*(2), 147-158. https://doi.org/10.1007/s40279-013-0107-0

Renfree, A., & St. Clair Gibson, A. (2013). Influence of Different Performance Levels on Pacing Strategy During the Women's World Championship Marathon Race. *International Journal of Sports Physiology and Performance, 8*(3), 279-285. https://doi.org/10.1123/ijspp.8.3.279

Robertson, C. V., Immink, M. A., & Marino, F. E. (2016). Exogenous Cortisol Administration; Effects on Risk Taking Behavior, Exercise Performance, and Physiological and Neurophysiological Responses. *Frontiers in Physiology, 7*. https://doi.org/10.3389/fphys.2016.00640

Robertson, C. V., & Marino, F. E. (2016). A Role for the Prefrontal Cortex in Exercise Tolerance and Termination. *Journal of Applied Physiology, 120*(4), 464-466. https://doi.org/10.1152/japplphysiol.00363.2015

Roebers, C. M. (2017). Executive Function and Metacognition: Towards a Unifying Framework of Cognitive Self-Regulation. *Developmental Review, 45*, 31-51. https://doi.org/10.1016/j.dr.2017.04.001

Rooks, C. R., Thom, N. J., McCully, K. K., & Dishman, R. K. (2010). Effects of

Incremental Exercise on Cerebral Oxygenation Measured by Near-Infrared Spectroscopy: A Systematic Review. *Progress in Neurobiology, 92*(2), 134-150. https://doi.org/10.1016/j.pneurobio.2010.06.002

Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive Control of Cognitive Processes in Task Switching. *Journal of Experimental Psychology: Human Perception and Performance, 27*(4), 763-797. https://doi.org/10.1037/0096-1523.27.4.763

Rushall, B. S., Hall, M., Roux, L., Sasseville, J., & Rushall, A. C. (1988). Effects of Three Types of Thought Content Instructions on Skiing Performance. *The Sport Psychologist, 2*(4), 283-297. https://doi.org/10.1123/tsp.2.4.283

Samson, A., Simpson, D., Kamphoff, C., & Langlier, A. (2017). Think aloud: An Examination of Distance Runners’ Thought Processes. *International Journal of Sport and Exercise Psychology, 15*(2), 176-189. https://doi.org/10.1080/1612197X.2015.1069877

Sandals, L. E., Wood, D. M., Draper, S. B., & James, D. V. B. (2006). Influence of Pacing Strategy on Oxygen Uptake During Treadmill Middle-Distance Running. *International Journal of Sports Medicine, 27*(1), 37-42. https://doi.org/10.1055/s-2005-837468

Santos-Concejero, J., Billaut, F., Grobler, L., Oliván, J., Noakes, T. D., & Tucker, R. (2015). Maintained Cerebral Oxygenation During Maximal Self-Paced Exercise in Elite Kenyan Runners. *Journal of Applied Physiology, 118*(2), 156-162. https://doi.org/10.1152/japplphysiol.00909.2014

Santos-Concejero, J., Billaut, F., Grobler, L., Oliván, J., Noakes, T. D., & Tucker, R. (2017). Brain Oxygenation Declines in Elite Kenyan Runners During A Maximal Interval Training Session. *European Journal of Applied Physiology, 117*(5), 1017-1024. https://doi.org/10.1007/s00421-017-3590-4

Sauter, M., Draschkow, D., & Mack, W. (2020). Building, Hosting and Recruiting: A Brief Introduction to Running Behavioral Experiments Online. *Brain Sciences, 10*(4), 251. https://doi.org/10.3390/brainsci10040251

Schücker, L., Fleddermann, M., de Lussanet, M., Elischer, J., Böhmer, C., &

Zentgraf, K. (2016). Focusing Attention on Circular Pedaling Reduces Movement Economy in Cycling. *Psychology of Sport and Exercise, 27*, 9-17. https://doi.org/10.1016/j.psychsport.2016.07.002

Schweizer, G., & Furley, P. (2016). Reproducible Research in Sport And Exercise Psychology: The Role of Sample Sizes. *Psychology of Sport and Exercise*, *23*, 114-122. https://doi.org/10.1016/J.PSYCHSPORT.2015.11.005

Seli, P., Carriere, J. S. A., & Smilek, D. (2015). Not All Mind Wandering is Created Equal: Dissociating Deliberate From Spontaneous Mind Wandering. *Psychological Research*, *79*(5), 750-758. https://doi.org/10.1007/s00426-014-0617-x

Shannon, O. M., Duckworth, L., Barlow, M. J., Deighton, K., Matu, J., Williams, E. L., Woods, D., Xie, L., Stephan, B. C. M., Siervo, M., & O'Hara, J. P. (2017). Effects of Dietary Nitrate Supplementation on Physiological Responses, Cognitive Function, and Exercise Performance at Moderate and Very-High Simulated Altitude. *Frontiers in Physiology*, *8*. https://doi.org/10.3389/fphys.2017.00401

Shaw, K., Singh, J., Sirant, L., Neary, J. P., & Chilibeck, P. D. (2020). Effect of Dark Chocolate Supplementation on Tissue Oxygenation, Metabolism, and Performance in Trained Cyclists at Altitude. *International Journal of Sport Nutrition and Exercise Metabolism, 30*(6), 420-426. https://doi.org/10.1123/ijsnem.2020-0051

Sibley, B. A., Etnier, J. L., & Le Masurier, G. C. (2006). Effects of an Acute Bout of Exercise on Cognitive Aspects of Stroop Performance. *Journal of Sport and Exercise Psychology, 28*(3), 285-299. https://doi.org/10.1123/jsep.28.3.285

Smith, B., & McGannon, K. R. (2018). Developing Rigor in Qualitative Research: Problems and Opportunities Within Sport and Exercise Psychology. *International Review of Sport and Exercise Psychology, 11*(1), 101-121. https://doi.org/10.1080/1750984X.2017.1317357

Smith, M. R., Marcora, S. M., & Coutts, A. J. (2015). Mental Fatigue Impairs Intermittent Running Performance. *Medicine & Science in Sports & Exercise, 47*(8), 1682-1690. https://doi.org/10.1249/mss.0000000000000592

Smits, B. L. M., Polman, R. C. J., Otten, B., Pepping, G.-J., & Hettinga, F. J. (2016). Cycling in the Absence of Task-Related Feedback: Effects on Pacing and Performance. *Frontiers in Physiology, 7*. https://doi.org/10.3389/fphys.2016.00348

Socci, V., Tempesta, D., Desideri, G., De Gennaro, L., & Ferrara, M. (2017). Enhancing Human Cognition with Cocoa Flavonoids. *Frontiers in Nutrition, 4*. https://doi.org/10.3389/fnut.2017.00019

Sparks, A., Williams, E., Jones, H., Bridge, C., & Marchant, D. (2016). Test-Retest Reliability Of A 16.1 Km Time Trial In Trained Cyclists Using The Computrainer Ergometer. *Journal of Science and Cycling, 5*(3), 35-41

St. Clair Gibson, A., De Koning, J. J., Thompson, K. G., Roberts, W. O., Micklewright, D., Raglin, J., & Foster, C. (2013). Crawling to the Finish Line: Why do Endurance Runners Collapse?: Implications for Understanding of Mechanisms Underlying Pacing and Fatigue. *Sports Medicine, 43*(6), 413-424. https://doi.org/10.1007/s40279-013-0044-y

St. Clair Gibson, A., Lambert, E. V., Rauch, L. H. G., Tucker, R., Baden, D. A., Foster, C., & Noakes, T. D. (2006). The Role of Information Processing Between the Brain and Peripheral Physiological Systems in Pacing and Perception of Effort. *Sports Medicine, 36*(8), 705-722. https://doi.org/10.2165/00007256-200636080-00006

St. Clair Gibson, A., & Noakes, T. D. (2004). Evidence for Complex System Integration and Dynamic Neural Regulation of Skeletal Muscle Recruitment During Exercise in Humans. *British Journal of Sports Medicine, 38*(6), 797-806. https://doi.org/10.1136/bjsm.2003.009852

St. Clair Gibson, A., Swart, J., & Tucker, R. (2018). The Interaction of Psychological and Physiological Homeostatic Drives and Role of General Control Principles in the Regulation of Physiological Systems, Exercise and the Fatigue Process - the Integrative Governor Theory. *European Journal of Sport Science, 18*(1), 25-36. https://doi.org/10.1080/17461391.2017.1321688

Strangman, G., Culver, J. P., Thompson, J. H., & Boas, D. A. (2002). A Quantitative Comparison of Simultaneous BOLD fMRI and NIRS Recordings during

Functional Brain Activation. *NeuroImage, 17*(2), 719-731. https://doi.org/10.1006/nimg.2002.1227

Subudhi, A. W., Miramon, B. R., Granger, M. E., & Roach, R. C. (2009). Frontal and Motor Cortex Oxygenation During Maximal Exercise in Normoxia and Hypoxia. *Journal of Applied Physiology, 106*(4), 1153-1158. https://doi.org/10.1152/japplphysiol.91475.2008

Sudo, M., Komiyama, T., Aoyagi, R., Nagamatsu, T., Higaki, Y., & Ando, S. (2017). Executive Function After Exhaustive Exercise. *European Journal of Applied Physiology, 117*(10), 2029-2038. https://doi.org/10.1007/s00421-017-3692-z

Swart, J., Lindsay, T. R., Lambert, M. I., Brown, J. C., & Noakes, T. D. (2012). Perceptual Cues in the Regulation of Exercise Performance - Physical Sensations of Exercise and Awareness of Effort Interact as Separate Cues. *British Journal of Sports Medicine, 46*(1), 42-48. https://doi.org/10.1136/bjsports-2011-090337

Swart, J., Tucker, R., Lamberts, R. P., Albertus-Kajee, Y., & Lambert, M. I. (2008). Potential Causes of Chronic Anterior Knee Pain in a Former Winner of the Tour de France. *International SportMed Journal, 9*(4), 162-171.

Tabachnick, B. G., Fidell, L. S., & Ullman, J. B. (2013). *Using multivariate statistics* (Vol. 6, pp. 497-516). Boston, MA: Pearson.

Tachtsidis, I., Elwell, C. E., Leung, T. S., Lee, C.-W., Smith, M., & Delpy, D. T. (2004). Investigation of Cerebral Haemodynamics by Near-Infrared Spectroscopy in Young Healthy Volunteers Reveals Posture-Dependent Spontaneous Oscillations. *Physiological Measurement, 25*(2), 437-445. https://doi.org/10.1088/0967-3334/25/2/003

Tempest, G. D., Davranche, K., Brisswalter, J., Perrey, S., & Radel, R. (2017). The Differential Effects of Prolonged Exercise Upon Executive Function and Cerebral Oxygenation. *Brain and Cognition, 113*, 133-141. https://doi.org/10.1016/j.bandc.2017.02.001

Tempest, G. D., Eston, R. G., & Parfitt, G. (2014). Prefrontal Cortex Haemodynamics and Affective Responses During Exercise: A Multi-Channel

Near Infrared Spectroscopy Study. *PLoS ONE, 9*(5), e95924. https://doi.org/10.1371/journal.pone.0095924

Tempest, G. D., & Parfitt, G. (2013). Imagery Use and Affective Responses During Exercise: An Examination of Cerebral Hemodynamics Using Near-Infrared Spectroscopy. *Journal of Sport and Exercise Psychology*, *35*(5), 503-513. https://doi.org/10.1123/jsep.35.5.503

Tempest, G. D., & Parfitt, G. (2016). Self-Reported Tolerance Influences Prefrontal Cortex Hemodynamics and Affective Responses. *Cognitive, Affective, & Behavioral Neuroscience, 16*(1), 63-71. https://doi.org/10.3758/s13415-015-0374-3

Thomas, R., & Stephane, P. (2007). Prefrontal Cortex Oxygenation and Neuromuscular Responses to Exhaustive Exercise. *European Journal of Applied Physiology*, *102*(2), 153-163. https://doi.org/10.1007/s00421-007-0568-7

Thompson, K., MacLaren, D., Lees, A., & Atkinson, G. (2003). The Effect of Even, Positive and Negative Pacing on Metabolic, Kinematic and Temporal Variables During Breaststroke Swimming. *European Journal of Applied Physiology, 88*(4), 438-443. https://doi.org/10.1007/s00421-002-0715-0

Thompson Coon, J., Boddy, K., Stein, K., Whear, R., Barton, J., & Depledge, M. H. (2011). Does Participating in Physical Activity in Outdoor Natural Environments Have a Greater Effect on Physical and Mental Wellbeing Than Physical Activity Indoors? A Systematic Review. *Environmental science & technology*, *45*(5), 1761-1772. https://doi.org/10.1021/es102947t

Tillman, C. M., & Wiens, S. (2011). Behavioral and ERP Indices of Response Conflict in Stroop and Flanker Tasks. *Psychophysiology, 48*(10), 1405–1411. https://doi.org/10.1111/J.1469-8986.2011.01203.X

Tisdall, M. M., Taylor, C., Tachtsidis, I., Leung, T. S., Elwell, C. E., & Smith, M. (2009). The Effect on Cerebral Tissue Oxygenation Index of Changes in the Concentrations of Inspired Oxygen and End-Tidal Carbon Dioxide in Healthy Adult Volunteers. *Anesthesia & Analgesia*, *109*(3), 906-913. https://doi.org/10.1213/ane.0b013e3181aedcdc

Tomporowski, P. D. (2003). Effects of Acute Bouts of Exercise on Cognition. *Acta Psychologica*, *112*(3), 297-324. https://doi.org/10.1016/S0001-6918(02)00134-8

Tønnessen, E., Sylta, Ø., Haugen, T. A., Hem, E., Svendsen, I. S., & Seiler, S. (2014). The Road to Gold: Training and Peaking Characteristics in the Year Prior to a Gold Medal Endurance Performance. *PloS one*, *9*(7), e101796. https://doi.org/10.1371/journal.pone.0101796

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D. J., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., … Straus, S. E. (2018). PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. *Annals of Internal Medicine, 169*(7), 467-473. https://doi.org/10.7326/m18-085

Tucker, R., Lambert, M. I., & Noakes, T. D. (2006). An Analysis of Pacing Strategies During Men's World-Record Performances in Track Athletics. *International Journal of Sports Physiology and Performance, 1*(3), 233-245. https://doi.org/10.1123/ijspp.1.3.233

Uludağ, K., Steinbrink, J., Villringer, A., & Obrig, H. (2004). Separability and Cross Talk: Optimizing Dual Wavelength Combinations for Near-Infrared Spectroscopy of the Adult Head. *NeuroImage, 22*(2), 583-589. https://doi.org/10.1016/j.neuroimage.2004.02.023

Umebayashi, K., & Okita, T. (2010). An ERP Investigation of Task Switching Using a Flanker Paradigm. *Brain Research*, *1346*, 165-173. https://doi.org/10.1016/J.BRAINRES.2010.05.050

Van Biesen, D., Mactavish, J., McCulloch, K., Lenaerts, L., & Vanlandewijck, Y. C. (2016). Cognitive Profile of Young Well-Trained Athletes With Intellectual Disabilities. *Research in Developmental Disabilities*, *53-54*, 377-390. https://doi.org/10.1016/j.ridd.2016.03.004

Van Cutsem, J., Marcora, S., De Pauw, K., Bailey, S., Meeusen, R., & Roelands, B. (2017). The Effects of Mental Fatigue on Physical Performance: A Systematic Review. *Sports Medicine*, *47*(8), 1569-1588. https://doi.org/10.1007/s40279-016-0672-0

Vanhatalo, A., Fulford, J., Bailey, S. J., Blackwell, J. R., Winyard, P. G., & Jones, A. M. (2011). Dietary Nitrate Reduces Muscle Metabolic Perturbation and Improves Exercise Tolerance in Hypoxia: Dietary Nitrate and Exercise in Hypoxia. *The Journal of Physiology, 589*(22), 5517-5528. https://doi.org/10.1113/jphysiol.2011.216341

van Ingen Schenau, G. J., de Koning, J. J., & de Groot, G. (1992). The Distribution of Anaerobic Energy in 1000 and 4000 Metre Cycling Bouts. *International Journal of Sports Medicine, 13*(06), 447-451. https://doi.org/10.1055/s-2007-1021296

Velasco, F., & Jorda, R. (2020). Portrait of Boredom Among Athletes and Its Implications in Sports Management: A Multi-Method Approach. *Frontiers in Psychology, 11*. https://doi.org/10.3389/fpsyg.2020.00831

Venhorst, A., Micklewright, D. P., & Noakes, T. D. (2018). The Psychophysiological Determinants of Pacing Behaviour and Performance During Prolonged Endurance Exercise: A Performance Level and Competition Outcome Comparison. *Sports Medicine, 48*(10), 2387-2400. https://doi.org/10.1007/s40279-018-0893-5

Villringer, A., Planck, J., Hock, C., Schleinkofer, L., & Dirnagl, U. (1993). Near Infrared Spectroscopy (NIRS): A New Tool to Study Hemodynamic Changes During Activation of Brain Function in Human Adults. *Neuroscience Letters, 154*(1-2), 101-104. https://doi.org/10.1016/0304-3940(93)90181-j

Vissing, J., Andersen, M., & Diemer, N. H. (1996). Exercise-Induced Changes in Local Cerebral Glucose Utilization in the Rat. *Journal of Cerebral Blood Flow & Metabolism, 16*(4), 729-736. https://doi.org/10.1097/00004647-199607000-00025

Walker, P. (2017). *RideLondon weekend attracts 100,000 cyclists to capital's streets*. The Guardian. https://www.theguardian.com/lifeandstyle/2017/jul/30/ridelondon-event-sees-100000-cycle-capitals-streets

Wallace, P. J., McKinlay, B. J., Coletta, N. A., Vlaar, J. I., Taber, M. J., Wilson, P. M., & Cheung, S. S. (2017). Effects of Motivational Self-Talk on Endurance and Cognitive Performance in the Heat. *Medicine & Science in Sports & Exercise, 49*(1), 191-199. https://doi.org/10.1249/mss.0000000000001087

Weich, C., Schüler, J., & Wolff, W. (2022). 24 Hours on the Run—Does Boredom Matter for Ultra-Endurance Athletes' Crises? *International Journal of Environmental Research and Public Health, 19*(11), 6859. https://doi.org/10.3390/ijerph19116859

Whitehead, A. E., Jones, H. S., Williams, E. L., Dowling, C., Morley, D., Taylor, J. A., & Polman, R. C. (2017). Changes in cognition over a 16.1 km cycling time trial using Think Aloud protocol: Preliminary evidence. *International Journal of Sport and Exercise Psychology, 17*(3), 266-274. https://doi.org/10.1080/1612197X.2017.1292302

Whitehead, A. E., Jones, H. S., Williams, E. L., Rowley, C., Quayle, L., Marchant, D., & Polman, R. C. (2018). Investigating the Relationship Between Cognitions, Pacing Strategies and Performance in 16.1 km Cycling Time Trials Using a Think Aloud Protocol. *Psychology of Sport and Exercise, 34,* 95-109. https://doi.org/10.1016/j.psychsport.2017.10.001

Whitehead, A. E., Montgomery, C., Swettenham, L., & Robinson, N. J. (2022). The Effect of Think Aloud on Performance and Brain Oxygenation During Cycling - An Exploratory Study. *Perceptual and Motor Skills, 129*(4), 1115-1136. https://doi.org/10.1177/00315125221104769

Whitehead, A. E., Taylor, J. A., & Polman, R. C. J. (2015). Examination of the Suitability of Collecting in Event Cognitive Processes Using Think Aloud Protocol in Golf. *Frontiers in Psychology, 6.* https://doi.org/10.3389/fpsyg.2015.01083

Wilberg, R. B., & Pratt, J. (1988). A Survey of the Race Profiles of Cyclists in the Pursuit and Kilo Track Events. *Canadian journal of sport sciences, 13*(4), 208-213.

Williams, E. L., Jones, H. S., Andy Sparks, S., Marchant, D. C., Midgley, A. W., & Mc Naughton, L. R. (2015). Competitor Presence Reduces Internal Attentional Focus and Improves 16.1 km Cycling Time Trial Performance. *Journal of Science and Medicine in Sport, 18*(4), 486-491.

https://doi.org/10.1016/j.jsams.2014.07.003

Williamson, J. W., McColl, R., Mathews, D., Mitchell, J. H., Raven, P. B., & Morgan, W. P. (2001). Hypnotic Manipulation of Effort Sense During Dynamic Exercise: Cardiovascular Responses and Brain Activation. *Journal of Applied Physiology, 90*(4), 1392-1399. https://doi.org/10.1152/jappl.2001.90.4.1392

Williamson, J. W., McColl, R., Mathews, D., Mitchell, J. H., Raven, P. B., & Morgan, W. P. (2002). Brain Activation by Central Command During Actual and Imagined Handgrip Under Hypnosis. *Journal of Applied Physiology, 92*(3), 1317-1324. https://doi.org/10.1152/japplphysiol.00939.2001

Wingfield, G., Marino, F. E., & Skein, M. (2018). The Influence of Knowledge of Performance Endpoint on Pacing Strategies, Perception of Effort, and Neural Activity During 30-km Cycling Time Trials. *Physiological Reports, 6*(21), e13892. https://doi.org/10.14814/phy2.13892

Wingfield, G., Marino, F. E., & Skein, M. (2019). Deception of Cycling Distance on Pacing Strategies, Perceptual Responses, and Neural Activity. *Pflügers Archiv - European Journal of Physiology, 471*(2), 285-299. https://doi.org/10.1007/s00424-018-2218-9

Wolff, W., & Martarelli, C. S. (2020). Bored Into Depletion? Toward a Tentative Integration of Perceived Self-Control Exertion and Boredom as Guiding Signals for Goal-Directed Behavior. *Perspectives on Psychological Science, 15*(5), 1272-1283. https://doi.org/10.1177/1745691620921394

Woods, D. R., O'Hara, J. P., Boos, C. J., Hodkinson, P. D., Tsakirides, C., Hill, N. E., Jose, D., Hawkins, A., Phillipson, K., Hazlerigg, A., Arjomandkhah, N., Gallagher, L., Holdsworth, D., Cooke, M., Green, N. D. C., & Mellor, A. (2017). Markers of Physiological Stress During Exercise Under Conditions of Normoxia, Normobaric Hypoxia, Hypobaric Hypoxia, and Genuine High Altitude. *European Journal of Applied Physiology, 117*(5), 893-900. https://doi.org/10.1007/s00421-017-3573-5

Wulf, G. (2013). Attentional Focus and Motor Learning: A Review of 15 Years. *International Review of Sport and Exercise Psychology, 6*(1), 77-104. https://doi.org/10.1080/1750984x.2012.723728

Wulf, G., & Lewthwaite, R. (2016). Optimizing Performance Through Intrinsic Motivation and Attention for Learning: The OPTIMAL Theory of Motor Learning. *Psychonomic Bulletin & Review*, *23*(5), 1382-1414. https://doi.org/10.3758/s13423-015-0999-9

Zhou, H., & Fishbach, A. (2016). The Pitfall of Experimenting on the Web: How Unattended Selective Attrition Leads to Surprising (Yet False) Research Conclusions. *Journal of Personality and Social Psychology*, *111*(4), 493-504. https://doi.org/10.1037/PSPA0000056

Zoladz, J. A., Pilc, A., Majerczak, J., Grandys, M., Zapart-Bukowska, J., & Duda, K. (2008). Endurance Training Increases Plasma Brain-Derived Neurotrophic Factor Concentration in Young Healthy Men. *Journal of Physiology and Pharmacology*, *59*(Suppl 7), 119-132.

Supplementary Materials

Item 1. A Screenshot of the Racermate Visual Screen Display.

Item 2. Think Aloud Practice Exercises Script

Task 1. "As part of this research, we are interested in capturing the thought processes of endurance performers. Thus, for one cycling time-trial to be completed, you will be instructed to think aloud whilst doing so. Think aloud requires a concurrent verbal report of your thought processes. To follow your thoughts, we would like you to verbalize everything that passes through your head. Do not try and explain anything, pretend there is no one here but yourself. The key thing is to think aloud constantly."

"I have some exercises for you to complete. Please try and think aloud, as described, as you work through completing the tasks":

(a) Math problem: "I would like you to think aloud as you multiply 19 by 6 in your head."

(b) Anagram: "Now I would like you to solve an anagram. I will show you a card with scrambled letters; it is your task to find an English word that consists of all the presented letters."

KORO = ROOK

NPHEPA = HAPPEN

CKHNCIE = CHICKEN

(c) Naming/free association task: "Now I would like you to think aloud as you name twenty different animals. Simply verbalize what passes through your mind as you name them."

Extra practice trials, if deemed necessary:

(d) "What animals would you expect to find in a zoo?"

(e) "What is the sixth letter before Q in the alphabet?"

Task 2. "I would like to you to practice using think aloud, as described, during exercise before participating in the TA time-trial."

Item 3. Secondary Theme Selection

Secondary themes were selected on theoretical premises reinforced by empirical research. Secondary themes analysed were distance, intentional distraction, involuntary distraction, motivation, pace (pace, increase pace, and decrease pace verbalizations combined), pain, and power output (PO). Firstly, *distance* covered and end-point knowledge are key sources of feedback used to optimize pacing according to popular models of endurance performance (e.g., the central governor model: Noakes, 2004; the psychobiological model: Marcora, 2010). Following on, research has suggested that *motivation* can be boosted by self-talk to improve cycling performance (Barwood et al., 2015). Moreover, awareness of *pacing* and the *self-regulation* of effort are encapsulated by metacognitive frameworks of endurance performance (Brick, MacIntyre, et al., 2016) and propositional work arguing for the importance of executive control in self-regulating effort (Hyland-Monks et al., 2018). The usage of *PO* feedback to gauge effort is related to pacing and *motivational* thought processes (Whitehead et al., 2018) and top-down executive control at the neuropsychological level (Wingfield et al., 2018). Finally, *intentional* and *involuntary distraction* were included as research has highlighted an external-to-internal shift in focus as exercise intensity increases and interoceptive cues (e.g., muscular *pain*) become more salient (Hutchinson & Tenenbaum, 2007). In conjunction with the above, thought processes in a positive and negative affective state were analysed as the reticular-activating hypofrontality model (Dietrich & Audiffren, 2011) points to a downregulation in brain areas involved in higher-order cognition (i.e., the prefrontal cortex) to regions more important for the control of movement during exercise. Consequently, top-down regulation, and therefore regulation of pace is possibly compromised when exercise intensity increases above the ventilatory threshold. The ventilatory threshold is suggested to be the point at which affective state transitions from being positive to negative (Ekkekakis et al., 2011).

References

Barwood, M. J., Corbett, J., Wagstaff, C. R. D., McVeigh, D., & Thelwell, R. C. (2015). Improvement of 10-km Time-Trial Cycling With Motivational Self-Talk Compared With Neutral Self-Talk. *International Journal of Sports Physiology and Performance*, *10*(2), 166–171. https://doi.org/10.1123/ijspp.2014-0059

Brick, N. E., MacIntyre, T. E., & Campbell, M. J. (2016). Thinking and Action: A Cognitive Perspective on Self-Regulation During Endurance Performance. *Frontiers in Physiology*, *7*(APR), 1–7. https://doi.org/10.3389/fphys.2016.00159

Dietrich, A., & Audiffren, M. (2011). The Reticular-Activating Hypofrontality (RAH) Model of Acute Exercise. *Neuroscience & Biobehavioral Reviews, 35*(6), 1305-1325. https://doi.org/10.1016/j.neubiorev.2011.02.00

Ekkekakis, P., Parfitt, G., & Petruzzello, S. J. (2011). The Pleasure and Displeasure People Feel When They Exercise at Different Intensities: Decennial Update and Progress Towards a Tripartite Rationale for Exercise Intensity Prescription. *Sports Medicine, 41*(8), 641-671. https://doi.org/10.2165/11590680-000000000-00000

Hutchinson, J. C., & Tenenbaum, G. (2007). Attention Focus During Physical Effort: The Mediating Role of Task Intensity. *Psychology of Sport and Exercise*, *8*(2), 233–245. https://doi.org/10.1016/j.psychsport.2006.03.006

Hyland-Monks, R., Cronin, L., McNaughton, L., & Marchant, D. (2018). The Role of Executive Function in the Self-Regulation of Endurance Performance: A Critical Review. *Progress in Brain Research, 240,* 353–370. https://doi.org/10.1016/bs.pbr.2018.09.011

Marcora, S. (2010). Counterpoint: Afferent Feedback From Fatigued Locomotor Muscles is Not an Important Determinant of Endurance Exercise Performance. *Journal of Applied Physiology*, *108*(2), 454–456. https://doi.org/10.1152/japplphysiol.00976.2009a

Noakes, T. D. (2004). From Catastrophe to Complexity: A Novel Model of Integrative Central Neural Regulation of Effort and Fatigue During Exercise in Humans. *British Journal of Sports Medicine, 38*(4), 511-514. https://doi.org/10.1136/bjsm.2003.009860

Whitehead, A. E., Jones, H. S., Williams, E. L., Rowley, C., Quayle, L., Marchant, D., & Polman, R. C. (2018). Investigating the Relationship Between Cognitions, Pacing Strategies and Performance in 16.1 km Cycling Time Trials Using a Think Aloud Protocol. *Psychology of Sport and Exercise, 34,* 95-109.

https://doi.org/10.1016/j.psychsport.2017.10.001

Wingfield, G., Marino, F., & Skein, M. (2018). The Influence of Knowledge of Performance Endpoint on Pacing Strategies, Perception of Effort, and Neural Activity During 30-km Cycling Time Trials. *Physiological Reports*, *6*(21), e13892. https://doi.org/10.14814/phy2.13892

Item 4. Mean (*SD*) Flanker Task Reaction Time and Accuracy by Stimuli, Session, Trial, and Trained Status.

Reaction time (ms)		**ET**		**Non-ET**	
		No TA	**TA**	**No TA**	**TA**
Congruent	Pre	393.29 (30.36)	388.43 (29.07)	400.00 (70.73)	389.98 (60.63)
	Post	362.78 (22.96)	374.89 (29.08)	374.88 (52.62)	380.10 (67.61)
Incongruent	Pre	450.49 (29.57)	447.56 (29.10)	457.93 (63.41)	446.12 (63.06)
	Post	420.13 (13.12)	424.14 (18.54)	428.71 (48.08)	431.95 (58.65)
Neutral	Pre	394.35 (28.10)	394.03 (28.29)	398.34 (61.32)	389.29 (56.35)
	Post	367.53 (20.14)	377.30 (24.42)	378.81 (50.62)	377.10 (63.51)

Accuracy (%)		**ET**		**Non-ET**	
		No TA	**TA**	**No TA**	**TA**
Congruent	Pre	.996 (0.011)	.996 (0.011)	.984 (0.035)	.993 (0.014)
	Post	.993 (0.014)	.994 (0.018)	.984 (0.035)	.981 (0.042)
Incongruent	Pre	.951 (0.030)	.966 (0.032)	.909 (0.131)	.920 (0.092)
	Post	.965 (0.025)	.939 (0.042)	.921 (0.094)	.925 (0.072)
Neutral	Pre	.993 (0.014)	.990 (0.019)	.981 (0.042)	.981 (0.042)
	Post	.993 (0.014)	.989 (0.016)	.974 (0.052)	.980 (0.035)

Note. Reaction time represents correct responses only. ET = endurance trained, Non-ET = non-endurance trained, No TA = No Think Aloud, TA = Think Aloud.