Exploring the Presence of Mental Fatigue in Elite Orienteering Training and Competition

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Abstract

Laboratory-based experiments have found that engaging in mentally demanding tasks can induce mental fatigue (MF), which is known to impair endurance and decision-making performance in sports. However, these experiments often lack ecological validity, and their generalisability is limited by individual differences in the perception of MF. These differences can be influenced by factors such as training level, environment, and occupation. Consequently, the transferability of findings from laboratory-based intervention to real-world sports settings may be limited. To address these limitations and improve our understanding of MF in applied sports contexts, this thesis explores how orienteers perceive and respond to MF in ecologically valid environments. This thesis comprises three studies investigating the presence and impact of MF in orienteering.

Study 1 employed a three-round online Delphi approach with 24 international orienteering athletes and practitioners to explore sport-specific perspectives on MF. The consensus reached in this study showed that international orienteering experts recognise the occurrence of MF during both orienteering training and competition, while also reinforcing differences in how MF is perceived between these contexts. However, there was no consensus that MF experienced in competition could be replicated in orienteering training. Furthermore, no consensus was reached on the existing definition of MF accurately reflects the MF experienced in orienteering. Consequently, a sport-specific definition of MF was developed to increase specificity and clarity in future research and support more accurate discussions of MF within the context of orienteering.

Study 2 analysed 43 orienteering races from 16 national-level orienteers and found a moderate increase in perceived MF (ES = 0.84 [0.49 , 1.19], mean difference: 19.7 [12.5 , 27.2]) following an orienteering competition. The increased MF ratings sustained up to 48 hours, with the perceived MF ratings remaining higher than pre-competition values to a small extent (ES = 0.54 [0.08 to 1.15], mean difference: 10.4 [-1.8 , 22.7]). These findings imply that orienteering competition can acutely induce perceived MF, with effects that may extend beyond the immediate post-competition period and influence recovery.

Study 3 examined the changes in perceived MF and other psychological responses among eleven national junior orienteers during a 4-day orienteering training camp. The combined analysis of 42 pre- and post-orienteering training responses found a moderate increase in perceived MF (ES = 1.06 [0.66 , 1.45], mean difference: 22.5 [15.6 , 29.5]). A moderate increase in perceived MF was observed following each training session, with a cumulative effect resulting in the highest MF ratings on the final day of the training camp. Importantly, perceived MF remained moderately elevated 48 hours after the termination of the orienteering training camp compared to the initial pre-camp ratings (ES = 0.86 [-0.07 , 1.75], mean difference 17.3 [-1.7 , 36.3]), suggesting that simulated orienteering training can also induce sustained MF.

Importantly, studies 2 and 3 revealed significant individual variability in perceived MF and related psychological responses such as physical fatigue, stress, tiredness, and mood states. These findings highlight that orienteers experience MF differently. The model comparison consistently supported the use of random intercept models that accounted for individual variability, emphasising the importance of considering variability between participants in statistical analyses. Furthermore, the differences in the magnitude and pattern of changes across outcome variables support the interpretation that MF is a different fatigue construct. Therefore, MF should be monitored and managed separately from other psychological responses.

In summary, this thesis provides evidence that both national and junior national-level orienteers experience MF during orienteering training and competition. This thesis advances the conceptual understanding of MF in orienteering by providing an orienteering-specific definition of MF and reinforces the importance of ecologically valid research designs that reflect the real-world experiences of athletes. Future research should investigate the acute and cumulative impact of MF on orienteering performance and recovery, as well as develop individualised strategies to monitor and manage MF alongside other psychological responses. This will be essential for optimising performance, recovery and fatigue management in orienteering.

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Chapter 6

List of Abbreviations

ACC	Anterior cingulate cortex
AX-CPT	AX-continuous performance task
BLa	Blood lactate
[BLa]	Blood lactate concentration
BRUMS	The Brunel Mood Scale
CON	Control group
CST	Congruent Stroop task
EEG	Electromyography
fMRI	Functional magnetic resonance imaging
fNIRS	Functional near-infrared spectroscopy
HR	Heart rate
HRR	Heart rate reserve
HRmax	Maximum heart rate
INT	Intervention group
IST	Incongruent Stroop task
kg	Kilogram
km	Kilometre
km.h-1	Kilometres per hour
La	Lactate
LMM	Linear mixed model
min	Minute
N/A	Not available
MF	Mental fatigue
MIST	Modified incongruent Stroop task

MVC	Maximal voluntary contraction
NASA-TLX	National Aeronautics and Space Administration Task Load Index
PF	Physical fatigue
POMS	Profile of mood states
RPE	Rating of perceived exertion
rpm	Revolutions per minute
RT	Reaction time
s	Seconds
SD	Standard deviation
SSG	Small-sided game
TT	Time-trial
TTE	Time-to-exhaustion
VAS	Visual Analogue Scale
VO_2 max	Maximum oxygen uptake
W	Watts
YYIRT1	Yo-Yo intermittent recovery test level 1

Publications and Presentations from this thesis

PEER-REVIEWED JOURNAL ARTICLES

1. **Lam, H. K. N.,** Sproule, J., Turner, A. P., Murgatroyd, P., Gristwood, G., Richards, H., & Phillips, S. M. (2023). International orienteering experts' consensus on the definition, development, cause, impact and methods to reduce mental fatigue in orienteering: A Delphi study. *Journal of Sports Sciences*, 40(23), 2595–2607. DOI: https://doi.org/10.1080/02640414. 2023.2177027

2. **Lam, H. K. N.,** Sproule, J., Turner, A. P., & Phillips, S. M. (2023). The impact of sprint, middle-distance, and long-distance orienteering races on perceived mental fatigue in national level orienteers. *Journal of Sports Sciences*, *41*(15), 1423-1436. DOI: https://doi.org/10.1080/02640414.2023.2273097

3. **Lam, H. K. N**., Sproule, J., Turner, A. P., & Phillips, S. M. (2024). Changes in perceived mental fatigue, physical fatigue and mood state during a 4-day national junior orienteering competition preparation camp, European Journal of Sport Science, 226-238, DOI: https://doi.org/10.1002/ejsc.12071

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1. **Lam, Hui Kwan Nicholas**; Sproule, John; Turner, Anthony P.; Murgatroyd, Paul; Gristwood, Graham; Richards, Hugh; Phillips, Shaun M. (2021) International Experts Consensus on the Development of Mental Fatigue in Orienteering: A Delphi study. *Poster presentation at the British Association of Sport and Exercise Sciences Conference 2021. Journal of sports sciences*, *39*(sup2), 1–66. https://doi.org/10.1080/02640414.2021.1978748 16-18 November 2021.

2. **Lam, Hui Kwan Nicholas**; Sproule, John; Turner, Anthony P.; Phillips, Shaun M. (2022) Changes in mental fatigue, physical fatigue and mood state during a two-day orienteering competition. *10-min Oral Presentation at the British Association of Sport and Exercise Sciences Conference 2022. Journal of sports sciences*, *40*(sup1), 1–39. https://doi.org/10.1080/02640414.2022.2125766 *King Power Stadium, Leicester, UK, 15-16 November 2022.*

3. **Lam, Hui Kwan Nicholas**; Sproule, John; Turner, Anthony P.; Phillips, Shaun M. (2023) Understanding the impact of mental fatigue: Competitive orienteering as a model for mental fatigue studies in military personnel. Poster presentation at the 6th International Congress on Soldier's Physical Performance. Excel - London, 12-14 September 2023.

Chapter 1: General Introduction

1.1 Background

There is growing evidence suggesting that prolonged periods of cognitively demanding activity can lead to impairment in both physical and cognitive performance, termed mental fatigue (MF). This impairment is defined as a psychobiological state that can negatively affect the execution of the tactical plan, endurance capacity, technical skills and decision-making performance (Van Cutsem et al., 2017; Cao et al., 2022; Habay et al., 2021; Sun et al., 2022; Brown et al., 2020). A recent meta-analysis concluded that MF has a small to moderate negative effect of MF on subsequent endurance capacity, motor performance, and both isometric and dynamic resistance performance (Brown et al., 2020). However, maximal anaerobic performance does not appear to be affected by MF (Brown et al., 2020). Further meta-analyses indicate that the cognitive effort required for a task may be a more determinant of MF than the duration of the task itself (Giboin et al., 2019; Brown et al., 2020).

While the evidence demonstrates that elevated subjective ratings of MF can negatively affect sport-specific performance such as tactical execution and technical skills (Habay et al., 2021; Sun et al., 2020), it is acknowledged that this MF was induced through computerised mental exertion task before measuring sport performance. These mental exertion tasks are designed to challenge an individual's response inhibition, sustained attention and self-regulation (Hotama et al., 2017; Coutinho et al., 2017; Pageaux et al., 2014; Martin et al., 2019). However, it remains unclear whether MF is limited to the preceding mental exertion task or if the act of engaging in the sport itself can also induce MF. Furthermore, previous research reports that well-trained individuals and those in occupations requiring high cognitive outputs may present higher resistance to experiencing MF (Martin et al., 2016; Martin et al., 2019). Previous research also suggests that the interpretation of fatigue including MF, can vary among individuals with different roles in sports (Russell et al., 2019), and the reliance on artificial MF protocol in the literature may hinder the understanding of MF within sporting populations. Without adequate observation of the development of MF during training and competition, it is challenging to determine when and how MF develops in sport. Previous observational studies with academy to elite soccer players (Thompson et al., 2020; Abbott et al., 2018; Abbott et al., 2020) and elite netball players (Russell et al., 2019; Russell et al., 2022) have demonstrated an acute increase in perceived MF following competition and training. However, sport-specific investigations are essential because the characteristics of each sport such as duration, physical and cognitive demands can vary, indicating findings from one sport may not directly apply to another. Consequently, recent research has attempted to investigate the perception of MF by interviewing athletes and practitioners (Russell et al., 2019; Thompson et al., 2021), acknowledging that the existing literature has yet to provide a clear rationale for the presence of MF in sports populations. The low ecological validity of the MF protocol used in the literature further complicates the understanding of MF in sports and hinders the development of effective management strategies for MF.

Considering that the interpretation of MF may vary as mentioned earlier, additional research is required due to the existence of various theoretical frameworks regarding the potential mechanism of MF (Boksem et al., 2006; Boksem & Tops, 2008; Martin et al., 2018; Smith et al., 2018). The conflicting theoretical frameworks limit the ability to understand and measure MF accurately. Importantly, fatigue is a complex phenomenon with the development of its dimensions potentially interlinked (Enoka & Duchateau, 2016; Behrens et al., 2023). Therefore, it is essential to investigate the underlying mechanism to determine the interactions among different types of fatigue, especially MF. Previous research assessing perceived MF during training and competition without the application of specific MF induction protocols has found an increase in perceived MF within sports (Thompson et al., 2020; Abbott et al., 2018, Abbott et al., 2022; Russell et al. 2021; Russell et al., 2022). This evidence suggests that should be to identify and determine the occurrence of MF in sports. Subsequently, exploring the relationship between MF and other fatigue-related variables is essential for gaining a comprehensive understanding of how MF affects an individual's psychological responses.

In orienteering, participants must constantly make precise decisions to navigate and plan the quickest route to the next control point, reacting to and reading the features of their surroundings using a map and compass (Batista et al., 2020; Batista et al., 2021). Previous research has found that completing a computerised mental exertion task before a simulated orienteering race can impair the completion time of orienteers (Batista et al., 2021). Orienteering is a perfect model for studying MF because the core elements of the sport expose orienteers to high physical and cognitive stress situations. Given that the understanding and interpretation of MF may vary across different sports (Russell et al., 2019), it is reasonable to investigate whether MF occurs naturally within the context of orienteering.

1.2 Future research requirements

Previous research summarised in section 1.1 indicates that MF induced through completing computerised MF protocols negatively affects sports performance. However, a major limitation of this evidence is its reliance on these computerised MF protocols, which may not effectively translate to real-world sporting contexts. While previous research has explored the natural occurrence of MF during training and competitions across various sports (Abbot et al., 2018; Abbott et al., 2020; Russell et al., 2021; Russell et al., 2022; Thompson et al., 2020), the understanding and interpretation of MF may differ among athletes and practitioners (Russell et al., 2019). This suggests that the unique characteristics of each sport can influence perceptions of MF, meaning that findings from one sport may not be directly applicable to other sports. Therefore, a specific investigation within the context of orienteering is required. Future research should adopt a similar approach to previous research (Russell et al., 2019; Russell et al., 2022; Thompson 2020). Firstly, it should investigate how experienced athletes and practitioners perceive MF in orienteering, and explore the presence of MF during training and competitions. This approach will help explain the relationship between perceived MF and other fatigue constructs, offering crucial empirical evidence on whether orienteers experienced MF during training and competitions. This would inform the development of effective fatigue monitoring and managing strategies.

1.3 Thesis Aim

The aim of this thesis is to explore the presence of MF in elite orienteers before, during, and after training and competitions.

Chapter 2: Literature Review

2.1 Fatigue in Sports: A Historical and Contemporary Perspectives

All literature searches in Chapter 2 of this thesis were conducted until 31 July 2023. Despite an extensive research history on fatigue (Giulio et al., 2006), a universally accepted definition of fatigue remains inconclusive. The lack of consensus is attributed to the multifaceted nature of fatigue and its varied applications across different fields. Firstly, the concept of fatigue is fragmented (Enoka & Duchateau, 2016), with different disciplines such as sports and clinical medicine developing their own definitions of fatigue to facilitate discipline-specific investigations. This approach resulted in a fragmented understanding of fatigue, potentially overlooking broader perspectives of fatigue. Secondly, the biological mechanisms underlying fatigue are complicated. Previous research indicates that fatigue may involve disruptions in neural signal transmission, from movement initiation to muscle contractile function, and at any stage of muscle contraction (Gandevia, 2001; Taylor et al., 2016). This complexity makes it challenging to determine a singular cause of fatigue across different contexts, leading researchers to conduct discipline-specific investigations rather than adopting a universal framework. Additionally, numerous factors further complicate the understanding of fatigue, including an individual's health and training history, environmental conditions, exercise intensity, exercise duration and muscle types. All these make it challenging to establish a unified definition, highlighting the importance of further research that integrates perspectives across disciplines.

Furthermore, the frequent interchangeability of "fatigue" with "exhaustion" has contributed to confusion in the literature. Exhaustion refers to a complete loss of function, whereas fatigue reflects a reduced capacity to maintain energy output at a given intensity (Marino et al., 2009; Ament et al., 2009). Consequently, the debate over the precise definition of fatigue largely depends on the focus of investigations in sports and exercise research. In sports science research, research primarily investigates the interaction between exercise physiology and psychology, aiming to understand how fatigue affects muscle contractile function and the neural drive from the central nervous system to the muscles. Within applied sports science, central fatigue and peripheral fatigue have been extensively studied, and these topics will be explored further in sections 2.1.1 and 2.1.2.

2.1.1 Central Fatigue

Central fatigue is defined as the fatigue happening within the central nervous system (CNS), particularly involving processes from the proximal to the neuromuscular junction, including the motor neurons, spinal nerves and brain (Gandevia, 2001; McMorris et al., 2018; Wan et al., 2017). Central fatigue influences the efficiency of signal transmission by motor neurons, thereby reducing the ability to optimally activate agonist muscles (Gandevia, 2001; Pageaux et al., 2013; Øvretveit & Laginestra, 2021). Central fatigue is associated with motor neuron excitability (Gandevia, 2001; Gandevia et al., 2013; Wan et al., 2017), indicating that decreased force production is not primarily due to a reduced ability to activate muscles but also results from impairment in neural excitability (Laurin et al., 2015). Consequently, central fatigue is often investigated by assessing high or low-frequency maximal voluntary activation of targeted muscles (Gandevia et al., 2013), which estimates the extent of voluntary recruitment of muscle fibres by participants. Additionally, the group III-IV muscle afferents have been implicated in central fatigue due to their role in providing sensory feedback to the CNS, thereby affecting the neural activation of muscles (Amann et al., 2020). However, it is important to recognise that group III-IV afferents primarily respond to mechanical stimuli within muscles (Taylor et al., 2016), which are not directly related to changes in the CNS. Therefore, discussing these sensory neurons such as group III-IV afferents in the context of central fatigue may be inappropriate because they are more relevant to peripheral fatigue, which will be discussed in section 2.1.2.

Furthermore, the physiological mechanisms underlying the decrease in maximal voluntary activation levels of the muscles remain unclear because multiple factors beyond neural excitability may contributed to reduced muscle activation following physical activity. For example, changes in brain glycogen concentration, dopamine (Meeusen et al., 2006) and brain oxygenation (Goodall et al., 2012) have also been suggested as potential contributors to central fatigue (Tornero-Aguilera et al., 2022; Meeusen & Roelands, 2018). Central fatigue is typically assessed through maximal voluntary contraction (MVC) in individuals (Gandevia et al., 2013; Le Mansec et al., 2018; Pageaux et al., 2013; Pageaux et al., 2015; Silva-Cavalcante et al., 2018); however, the exercise protocol utilised in these studies vary, which can affect the interpretation of the results. These exercise protocols often involve repeated MVC tests with different rest intervals. Previous research has acknowledged the technical difficulty in determining whether the inability to maintain maximal neural drive is attributed to a decrease in motivation to exert maximal effort or the presence of central fatigue (Davis & Bailey, 1997). Additionally, there is an ongoing debate about whether individuals can sustain maximal central nervous system drive to specific muscles even in highly motivated situations because many studies argue that recruiting all motor units during repeated MVC tests may not be feasible. Therefore, an explanation primarily based on the excitatory and inhibitory processes of the neurotransmitters may oversimplify the phenomenon. Further investigation is required to understand the extent to which neurotransmitters affect central fatigue.

A recent narrative review concluded that central fatigue is a more complex phenomenon than simply a decline in neuromuscular transmission (Tornero-Aguilera et al., 2022). This review summarises that central fatigue impairs the concentration of brain dopamine, gamma-aminobutyric acid, serotonin and glutamate, indicating that the origin of central fatigue may develop within the brain (Tornero-Aguilera et al., 2022). In addition to reducing muscle voluntary activation levels, central fatigue has also been associated with impaired sleep quality, reduced ability to maintain mental attention, cognitive vigilance, and an increased subjective feeling of fatigue (Tornero-Aguilera et al., 2022). These findings suggest that reduced voluntary muscle activation represents just one of several symptoms linked to central fatigue. To enhance understanding of how central fatigue develops, increasing evidence has used objective measurements of neurotransmitters, including serotonin (Coxon et al., 2018; Meeusen et al., 2021; Thorstensen et al., 2020), to examine the changes associated with central fatigue.

Due to the complex nature of fatigue, the explanation of central fatigue may overlap with peripheral fatigue, complicating the understanding of how central fatigue develops and is regulated within the body. Furthermore, factors beyond the central nervous system can affect the understanding and interpretation of central fatigue. Previous research has highlighted that individual variability including anatomical, physiological and neuromuscular differences, as well as perceptions of task complexity (Behrens et al., 2023; Tornero-Aguilera et al., 2022) can contribute to differences in experienced fatigue. Moreover, variations in fatigue tolerance between individuals pose a challenge to the validity of results, as these differences make it difficult to establish a standardised method for quantifying fatigue levels.

2.1.2 Peripheral Fatigue

Peripheral fatigue refers to the processes that occur within the muscles, from the distal to the neuromuscular junction, rather than originating in the CNS (Allen et al., 2008; Enoka & Duchateau, 2016; Taylor et al., 2016; Øvretveit & Laginestra, 2021). Previous research indicates that peripheral fatigue is closely related to metabolic changes within the working muscles, predominantly observed during high-intensity exercise (Taylor et al., 2016; Øvretveit & Laginestra, 2021). The delivery of oxygen to the muscles is a vital factor in the development of peripheral fatigue as both hyperoxia and hypoxic conditions can affect its occurrence (Øvretveit & Laginestra, 2021). The increased ATP demand during muscle contractions leads to the accumulation of inorganic phosphate, magnesium, lactate and calcium ions, as well as the depletion of glycogen, and the generation of reactive oxygen species (Tornero-Aguilera et al., 2022). Furthermore, exercise-induced fatigue can reduce the excitability and release of acetylcholine, together with reducing efficiency of calcium in controlling the muscle fibre activation at the neuromuscular junction (Allen et al. 2008). Consequently, these changes negatively affect muscle contractile function and reduce muscle force production. The role of oxygen in peripheral fatigue is supported by previous research demonstrating differences in cycling time-trial performances under different inspired oxygen fractions, while maintaining consistent central neural output (Amann et al., 2006). This reflects that peripheral fatigue acts as a protective mechanism to regulate muscle function and prevent physiological strain. However, it remains unclear whether a definitive threshold for peripheral fatigue exists, as previous research has found that the extent of fatigue varies depending on the task being performed (Hureau et al., 2018).

The amount of peripheral fatigue depends on the neural drive and firing rate of muscle fibres and is affected by the intensity, type and duration of the physical activity (Taylor et al., 2016). This process shares similarities with central fatigue, suggesting that central fatigue and peripheral fatigue may interact and mutually influence each other. The potential relationship between central fatigue and peripheral figure is displayed in Figure 2.1. An increased neural drive in group III/IV afferents provides feedback to the CNS, enabling the regulation of the cardiovascular and respiratory system to adjust the muscle firing rate and contractile function, thereby preventing physiological strain (Taylor et al., 2016). This feedback loop ensures that working muscles transmit signals to the CNS, which then regulates muscle blood flow and ventilation to meet the metabolic requirements of the task. The brain also sends feedforward signals to reduce unnecessary strain on the working muscles.

To elaborate, peripheral fatigue can be seen as a regulatory threshold that constantly provides feedback to the CNS regarding the mechanical and metabolic status of the working muscles. This process ensures that muscle functions remains within appropriate physiological limits. This supports the explanation that the relationship between peripheral fatigue and central fatigue may overlap, as mentioned in section 2.1.1 because peripheral fatigue occuring during physical activity may already be mediated by central fatigue in the brain. Central fatigue initially alters perceptions of effort and neuromuscular activation before reaching the point of peripheral contractile failure. However, it remains challenging to determine whether fatigue regulation is primarily a conscious decision where individuals adjust exercise intensity to optimise physiological capability, or whether individuals perceive they have reached their maximum physiological limit and thus choose to terminate the exercise. This complexity reinforces the idea that fatigue is an interlinked phenomenon, making it inappropriate to intentionally separating it into different constructs since they are intricately linked.

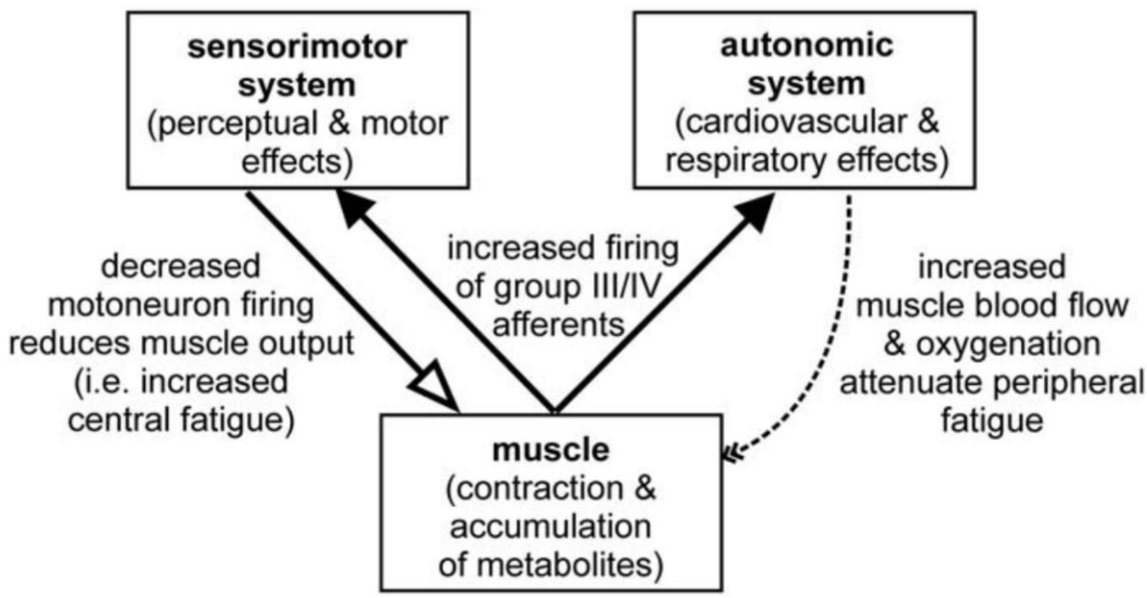

Figure 2.1 The potential interplay of the mechanism between central and peripheral fatigue (Figure extracted from Taylor et al., 2016).

2.1.3 Contemporary Conceptualisation of Fatigue

A proposed fatigue taxonomy by Enoka and Duchateau (2016) challenges the traditional approach to understanding fatigue, arguing that it should not be conceptualised based on the location of fatigue. According to Figure 2.2, fatigue should be viewed as two independent attributes: performance fatigability and perceived fatigability. Performance fatigability refers to the variables that can be measured objectively, such as muscle voluntary contraction, muscular force production and changes in neuromuscular transmission (Enoka & Duchateau, 2016; Behrens et al., 2023). This focuses on the physical and physiological capacities of the individuals. Conversely, perceived fatigability represents the subjective dimension of fatigue, encompassing the individual's perception and the regulation of their ability to complete the task. It includes the subjective feelings of tiredness, arousal, perceived intensity and motivation towards the task (Enoka & Duchateau, 2016; Behrens et al., 2023).

This proposed framework (Figure 2.2) provides a more effective interpretation of fatigue by separating it into subjective and objective experiences of fatigue. It allows for more accurate identification of the underlying causes of fatigue, thereby improving fatigue management strategies. For example, individuals reporting high perceived fatigability but low-performance fatigability may require appropriate psychological management rather than adjustments in physical workload. According to sections 2.1.1 and 2.1.2, the concepts of central fatigue and peripheral fatigue have primarily focused on performance fatigability while neglecting perceived fatigability. However, exploring the subjective dimension of fatigue is equally important, as it affects cognitive decision-making, especially in determining whether to continue or terminate the task. This fatigue taxonomy highlights the importance of measuring fatigue through both subjective and objective measures to advance fatigue assessment and management.

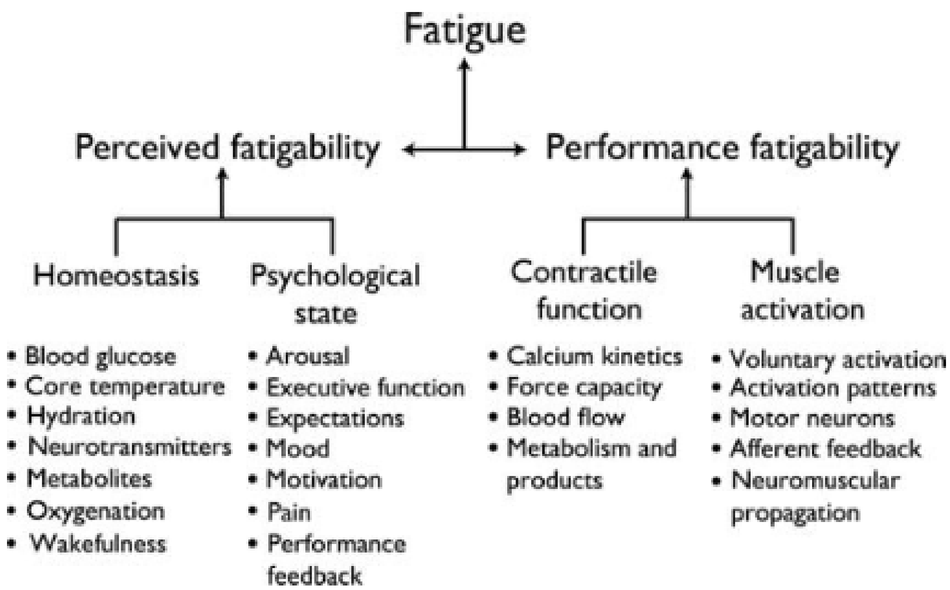

Figure 2.2 The proposed taxonomy of fatigue with the relevant modulating factors for performance fatigability and perceived fatigability (Figure extracted from Enoka & Duchateau, 2016).

2.1.4 Mental Fatigue

There is increasing evidence investigating the effects of MF in sports, as researchers suggest that perceptions of MF can influence perceived exertion in subsequent physical tasks (Van Cutsem et al., 2017). A key experiment in sports-related research conducted by Marcora et al. (2009) discovered that the ratings of perceived MF and cycling performance were negatively affected following the completion of a 90-minute computerised cognitively demanding task. These findings have gained research interest among sports scientists in exploring the psychological endurance of athletes in addition to the physiological aspect of athletes. Previous systematic reviews have concluded that MF can detrimentally affect both physical and cognitive performance (Van Cutsem et al., 2017; Habay et al., 2021; Sun et al., 2020). These findings has captured the attention of sports scientists as most sports require sustained periods of concentration to respond to various stimuli and make tactical decisions. Further details on the effects of MF on sports performance will be discussed in section 2.2. Additionally, recent research has begun to explore the management strategies for reducing MF in sports (Proost et al., 2022). This interest stems from previous research demonstrating that MF can accumulate during training or competition (Russell et al., 2022; Thompson et al., 2020; Abbott et al., 2020), potentially affecting the overall internal load of the athletes (Coyne et al., 2021). These findings highlight the importance of examining sports performance holistically, recognising MF as a potential influential factor that can affect both physical and cognitive performance.

According to section 2.1.1, central fatigue occurs within the central nervous system including both the brain and spinal cord. This fatigue is primarily associated with physical activities, where the presence of central fatigue can reduce the efficiency of muscle activation. In contrast, MF is often defined as a reduced willingness to exert additional effort when performing physical and/or cognitive work (Inzlicht & Marcora, 2016). Additionally, MF has been described as a delicate balance between motivation and the perceived effort required to complete a task, where the presence of MF may prompt individuals to shift their focus towards tasks offering more immediately rewarding outcomes (Inzlicht & Marcora, 2016). Although both central fatigue and MF can impair physical performance, the key difference between these two types of fatigue is the aggravating factor. MF is proposed to elicit following prolonged periods of cognitively demanding activity instead of physically demanding activity (Van Cutsem et al., 2017). The potential mechanism of MF will be discussed further in section 2.3. Additionally, there remain unresolved issues regarding MF, which will be addressed in sections 2.1.4 and 2.1.5.

It t is important to acknowledge that the literature contains multiple definitions of MF, and a universally standardised or accepted definition has yet to be identified. However, the concept of MF is largely associated with overloaded information processing, sustained attention, and the attentional demands arising from engagement in cognitively demanding tasks, which can result in impairments in perceived MF and sport-related physical and cognitive performance (Cao et al., 2022; Giboin & Wolff, 2019; Habay et al., 2021; Smith et al., 2018; Van Cutsem et al., 2017). While MF has been defined as a psychobiological state triggered by prolonged engagement in cognitively demanding tasks, affecting the physiological, behavioural and subjective aspects of individuals (Proost et al., 2022; Van Cutsem et al., 2017), it is important to emphasise that the presence of MF does not necessarily require impairment in all three dimensions. There may be compensatory effects that minimise the impact of MF on sports performance (Hopstaken et al., 2015; Möckel et al., 2015). Despite MF being proposed as a different fatigue construct that can be differentiated from other relevant fatigue concepts (Russell et al., 2022), it is crucial not to overlook fatigue as a multifaceted phenomenon that often interacts with and occurs alongside other forms of fatigue. Figure 2.3 presents the theoretical process of the development and impact of MF in sports.

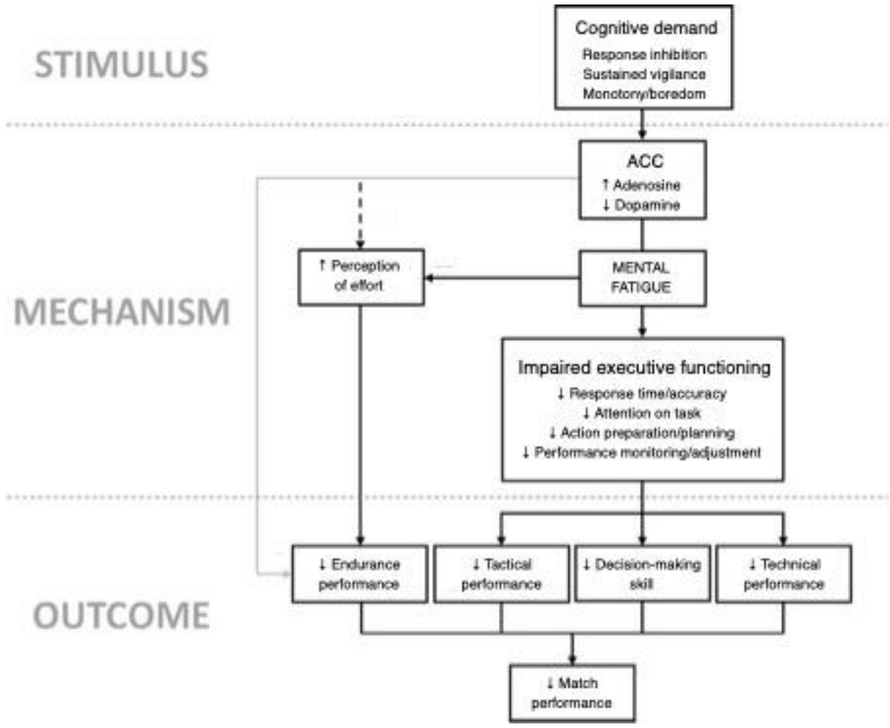

Figure 2.3 The theoretical process of the development and impact of MF in sports (Adapted from Smith et al. (2018) and modified as appropriate).

In contrast to other types of fatigue discussed previously, the negative effects of MF are primarily related to changes in behaviour rather than specific observable physiological output such as maximal power output. Mentally fatigued individuals tend to disengage early from tasks that involve conscious decision-making without reaching their maximal physiological tolerance, as demonstrated by altered self-pacing during endurance performance. Conversely, the presence of MF does not significantly affect anaerobic performance including maximal strength and power output as these activities involve minimal conscious decision-making (Van Cutsem et al., 2017). This highlighted that MF predominantly affects the cognitive processes, distinguishing it from other fatigue types. Further information regarding the negative effects on physiological and psychological responses will be discussed in sections 2.2 and 2.5, while proposed mechanisms of MF will be discussed in section 2.3. Moreover, previous research using self-report measures during training and competition discovered that athletes perceived MF as a different fatigue construct, with the ratings of perceived MF changing differently from physical fatigue, motivation and other psychological responses (Russell et al., 2019; Russell et al., 2022; Thompson et al., 2020). This suggests MF extends beyond mere psychological responses, requiring additional attention due to its pronounced negative influence on behavioural outcomes. Furthermore, a recent review found individual characteristics, such as gender and performance level, do not significantly affect susceptibility to MF (Habay et al., 2023), implying athletes can experience MF regardless of their training status. To elaborate, these findings show that both the aggravating factors and effects of MF differ from those associated with central fatigue and peripheral fatigue. Therefore, MF should be recognised as a different fatigue construct and requires independent investigation.

2.1.5 Unresolved issues related to mental fatigue

One of the controversial issues in the literature relates to the terminology used to describe the fatigue elicited by cognitively demanding activity. The debate centres around whether this type of fatigue should be termed as ‘mental fatigue’ or ‘cognitive fatigue’. Some researchers favour the term ‘cognitive fatigue’ because it directly refers to the impairment of the cognitive functions following cognitive tasks (Ackerman & Kanfer, 2009; Ackerman et al., 2010). Some studies have defined ‘cognitive fatigue’ as an acute decline in performance resulting from cognitive overload induced by cognitively demanding tasks (Head et al., 2016; MacMahon, Hawkins, & Schücker, 2019; MacMahon et al., 2014; McMorris, Barwood, & Corbett, 2018; McMorris et al., 2018). As discussed in previous research, the impairment following MF interventions has been associated with behavioural changes, reduced perceived motivation, and alterations in other psychological responses, including mood states (Boksem et al., 2006; Martin et al., 2018; Van Cutsem et al., 2017). However, the term ‘cognitive’ primarily focuses on cognition and neglects other vital components such as emotional states and overall well-being. It is crucial to emphasise that mentally fatigued individuals often experience mood disturbances following cognitively demanding tasks (Giboin & Wolff, 2019; Habay et al., 2021; Van Cutsem et al., 2017), highlighting the importance of incorporating emotional and psychological elements into the discussion of fatigue. Therefore, the term ‘cognitive fatigue’ may only encompass the fatigue associated with cognitive functions which may be inadequate in justifying the mental and emotional exhaustion experienced under MF conditions. Although the terminologies ‘cognitive fatigue’ and ‘mental fatigue’ have often been used interchangeably in the literature, the term ‘mental fatigue’ comprehensively captures both the cognitive impairment and associated changes in emotional and psychological states Consequently, the term ‘mental fatigue’ is utilised in this thesis.

Another debatable issue is the challenge of distinguishing whether an early disengagement in physical assessments results from reduced motivation, reduced goal-directed attention or MF, as reduced unwillingness to exert further effort can also be a sign of decreased motivation (Boksem et al., 2005; Boksem et al., 2006). However, previous research has reported that changes in motivation alone cannot adequately explain MF (Harris et al., 2021). For example, modifying incentives or rewards for subsequent physical performance, such as providing monetary incentives failed to mitigate impairments associated with MF (Boksem & Tops, 2008; Brown & Bray, 2017; Brown & Bray, 2018; Harris & Bray, 2021). While some studies have attempted to explain MF through motivational factors such as providing incentives or rewards (Boksem & Tops, 2008), evidence suggests reduced motivation should be considered as a consequence of MF instead of its underlying cause (Harris & Bray, 2019; Harris & Bray, 2021). Previous research found that mentally fatigued individuals tend to avoid vigorous physical activity (Harris & Bray, 2019). However, under conditions of high motivation, mentally fatigued individuals have shown a preference for selecting more physically demanding tasks compared to conditions without MF (Harris & Bray, 2021). Importantly, the overall amount of physical work completed did not significantly differ between these conditions (Harris & Bray, 2021). These findings reflect that increasing motivation through monetary incentives may influence individuals' intentions to engage in more challenging tasks, but it does not minimise the negative effects of MF. Although motivation plays a vital role in determining individuals' willingness to exert effort to complete tasks (Boksem et al., 2005, Boksem et al., 2006), most studies indicate that increased mental demand following an MF protocol does not significantly affect motivation towards subsequent physical tasks (MacMahon et al., 2014; Marcora et al., 2009; Pageaux et al., 2014; Salam et al., 2018; Smith et al., 2016; Smith et al., 2017; Van Cutsem et al., 2019; Veness et al., 2017). Therefore, relying on motivational changes to explain MF may introduce bias as incentives can affect decision-making in mentally fatigued individuals. Given the variability and limitations of existing MF theories, excluding irrelevant theories is essential to improve the clarity and methodological efficiency of future investigations.

Additionally, the definition of MF presented in section 2.1.4 appears insufficient for applied sports settings, as athletes and practitioners have different interpretations and understandings of MF (Thompson et al., 2020; Russell et al., 2019). Athletes and practitioners perceived that MF negatively affects their decision-making ability and psychological responses, highlighting that perceived MF can occur in a cumulative manner rather than solely as an acute experience

(Thompson et al., 2020; Russell et al., 2019). In contrast, laboratory-based research has primarily focused on the acute effects of MF, defining MF as a state elicited by performing prolonged periods of cognitively demanding tasks (Van Cutsem et al., 2017). However, applied work demonstrates that MF can develop both acutely and cumulatively, indicating a discrepancy between laboratory-based research and applied sporting environments. Therefore, the complex nature of MF experienced by athletes in real-world settings may not be fully captured by definitions derived solely from laboratory-based research. This inconsistency highlights the need for research methodologies that are more ecologically valid, including mixed-methods and field-based studies that work closely with athletes and practitioners. These approaches would facilitate a better understanding of the presence, perceptions, and influences of MF in applied sporting environments, while also allowing for meaningful comparisons with controlled laboratory-based findings. While laboratory-based research provides essential foundational knowledge of MF, its findings regarding the development and impact of MF should be interpreted with caution to enhance their relevance and applicability in real-world sports contexts.

2.2 Effects of Mental Fatigue on Physical and Cognitive Performance

2.2.1 Endurance Time Trial Performance

Eighteen studies discussed in this section are summarised in Table 2.1. Although 11 studies did not report significant impairment in subsequent TT performance following a MF protocol (Clark et al., 2019; Filipas et al., 2018; Fortes et al., 2020; Holgado et al., 2019; Martin et al., 2016; Pageaux et al., 2015; Roussey et al., 2018; Silva et al., 2018; Lam et al., 2021; Batista et al., 2021; Gattoni et al., 2021), nine studies reported a significant increase in subjective ratings of MF or mental demand. This reflects that participants still experienced MF following the MF protocol, but it did not statistically significantly affect subsequent TT performance. Moreover, two studies utilised different experimental settings from the majority of the studies in Table 2.1. One study performed the MF protocol and exercise testing simultaneously (Holgado et al., 2019), while another study did not manipulate any activity in the control group for comparison (Lam et al., 2021). These variations in experimental design could have contributed to the insignificant changes in TT performance. It is also crucial to highlight that MF is proposed to occur following a prolonged period of cognitively demanding activity (Van Cutsem et al., 2017). Holgado et al. (2019) is the only study to complete the MF protocol in a dynamic environment, requiring extra attentional resources from participants to perform the cognitively demanding activity. The increased subjective ratings of MF in this study may be attributed to the continuous switching of attentional focus between cognitive and physical tasks, rather than an increase in cognitive output.

Furthermore, four studies in Table 2.1 incorporated a low cognitive demand task, such as a congruent Stroop-colour task, in the control condition to minimise the potential differences between the control and MF conditions (Filipas et al., 2018; Holgado et al., 2019; Pageaux et al., 2014; Pageaux et al., 2015). However, only Pageaux et al. (2014) with 12 physically active individuals reported a significant decrease in subsequent TT performance between control and MF conditions. Conversely, the remaining studies involving recreationally active (Filipas et al., 2018; Pageaux et al., 2015) and trained population (Holgado et al., 2019) did not present impaired TT performance under the MF state. Consequently, it is challenging to conclude if the significant impairment in subsequent TT performance reported in Pageaux et al. (2014) was attributed to the mismatched experiment setting compared to other studies in Table 2.1, as similar experiments did not yield consistent results. The effect of protocol duration on MF will be discussed in section 2.4.2.

Aside from a significant increase in subjective ratings of MF, eight studies in Table 2.1 showed MF did not only affect TT performance but also impaired positive affect and vigour ratings (Filipas et al., 2019; MacMahon et al., 2014; Pageaux et al., 2014; Pires et al., 2018; Staiano et al., 2018). However, the absence of positive mood changes does not necessarily indicate the absence of negative effects of MF on subsequent TT performance (Brown et al., 2019; Martin et al., 2016; Penna et al., 2018b). Regarding the specificity of the TT assessment to the participants, 12 studies utilised a TT test specific to individual characteristics (Batista et al., 2021; Filipas et al., 2018; Filipas et al., 2019; Fortes et al., 2020; Gattoni et al., 2021; Holgado et al., 2019; Martin et al., 2016; Penna et al., 2018b; Pires et al., 2018; Roussey et al., 2018; Silva-Cavalcante et al., 2018; Staiano et al., 2018). However, nine out of these twelve studies showed no significant impairment in TT performance following MF intervention (Batista et al., 2021; Filipas et al., 2018; Filipas et al., 2019; Fortes et al., 2020; Gattoni et al., 2021; Holgado et al., 2019; Lam et al., 2021; Martin et al., 2016; Silva-Cavalcante 2018). Furthermore, the results are considered conflicting when the TT assessment did not match individual characteristics, as three of five studies did not demonstrate any impairment (Brown et al., 2018; Clark et al., 2019; Pageaux et al., 2015). Although no statistically significant differences were identified after MF intervention, well-trained orienteers presented an increase of 2.1 minutes in completion time for a subsequent 3.1km orienteering race (Batista et al., 2021). Similarly, amateur runners demonstrated an additional 4 minutes in subsequent half-marathon under mentally fatigued conditions (Gattoni et al., 2021). These findings imply that athletes may perform worse under the MF state, particularly in endurance running. It is crucial to highlight that the impairment caused by MF among orienteers is believed to be more pronounced, considering the relatively shorter race distance compared to a half marathon and the well-trained status of the participants, who were experienced orienteers rather than amateurs. However, the findings of Gattoni et al. (2021) should be interpreted with caution as the mean age of the participants was 43.8 ± 8.6, which is older than the majority of participants in the research listed in Table 2.1. It is unclear whether age affects the extent of MF experienced in sports, indicating the use of individual-specific TT assessment could improve the validity of the investigations.

Another observation among the studies listed in Table 2.1 is that the majority of the studies recruited participants ranging from untrained to professional levels. However, three studies investigated the youth population, with participants aged between 11 and 16 (Filipas et al., 2018; Penna et al., 2018b; Staiano et al., 2018). Interestingly, two of these studies found significant impairment in subsequent TT test performance following the MF protocol (Penna et al., 2018b; Staiano et al., 2018). These findings imply that actively trained youth, especially those engaged at the club level, may experience performance impairments under MF conditions, leading to slower completion times in the TT. However, it is important to acknowledge the lack of investigation on untrained youth populations, and further evidence is required to establish if age significantly influences the likelihood of experiencing MF. Moreover, in comparison to other evidence summarised in Table 2.1, it is observed that significant impairments were primarily observed in studies using untrained or recreationally trained individuals (Pires et al., 2018; Pageaux et al., 2014; Martin et al., 2016; MacMahon et al., 2014; Brown & Bray 2018). Conversely, the studies using well-trained or professional-level participants did not detect a significant impact of MF on TT performance (Silva et al., 2018; Roussey et al., 2018; Martin et al., 2016; Holgado et al., 2019; Fortes et al., 2020; Filipas et al., 2019). This result discrepancy suggests that well-trained individuals may have greater resilience to the effects of MF compared to recreationally trained and youth participants, potentially mitigating the negative influence of MF on subsequent TT performance.

As discussed above, individuals experienced varying degrees of impairment after experiencing MF, with only half of the included studies reporting a significant decrease in subsequent TT performance (Brown & Bray, 2018; Filipas et al., 2019; MacMahon et al., 2014; Pageaux et al., 2014; Penna et al., 2018b; Pires et al., 2018; Staiano et al., 2018). Table 2.1 demonstrates that most of the studies manipulated emotionally neutral videos or documentaries as a control condition for comparison (Brown et al., 2018; Clark et al., 2019; Filipas et al., 2019; Fortes et al., 2020; MacMahon et al., 2014; Martin et al., 2016; Pires et al., 2018; Roussey et al., 2018; Silva et al., 2018; Staiano et al., 2018; Penna et al., 2018b). The nature of the videos or documentaries is important, as previous research has found that the neutrality of the video can affect physical exertion and subsequent 10km cycling TT performance (Wagstaff, 2014). Given that emotions are entirely subjective, it is crucial to assess the neutrality of the videos or documentaries used in control conditions to minimise confounding variables. However, out of the twelve included studies, only Penna et al. (2018b) assessed the neutrality of the video in a pilot test and found no significant change in mood after 30 min of watching. The insignificant findings in subsequent TT performance following the MF protocol may be attributed to the experimental settings, as other studies did not assess the neutrality of the documentaries or videos with the participants beforehand. Therefore, it remains unclear whether the videos or documentaries in the control condition were emotionally neutral to the participants.

Another interesting observation is the transition period between the end of the MF protocol and the beginning of the endurance TT testing plays a significant role in investigating the effects of MF. Four out of five studies in Table 2.1 manipulated a relatively short transition period (≤ 5 mins) and showed a significant decrease in TT performance following the MF protocol (Brown et al., 2018; Filipas et al., 2019; MacMahon et al., 2014; Penna et al., 2018b). The remaining study reported a significant decrease only in the first 500m of a 4km cycling TT (Silva et al., 2018). In contrast, only three out of ten studies demonstrated a deleterious effect of MF on subsequent TT performance when the transition period was long (≥ 10 mins)(Pageaux et al., 2014; Pageaux et al., 2015; Martin et al., 2016). While Staiano et al. (2018) reported a significant decrease in 2km kayaking TT performance following a 60-minute, the duration of the transition period was not specified. These findings suggest that while MF can acutely affect TT performance, a transition period as short as 10 minutes may mediate some of the negative effects of MF. Some may argue that lengthening the transition period can reduce the effect of MF on TT performance; however, previous research indicates that the subjective rating of MF remained high even 60 minutes after completing a 45-minute computerised cognitively demanding task (Smith et al., 2019). Most studies in Table 2.1 reported higher perceived MF after the MF protocol, irrespective of the effect of MF on TT performance. Based on the evidence discussed above, although previous review have concluded that MF negatively affects endurance capacity (Van Cutsem et al., 2017), this thesis suggested that TT performance is significantly affected by MF. Therefore, standardising the transition period can lead to a more accurate evaluation of the impact of MF on TT performance.

Previous research has reported that monetary incentives could potentially reduce the deleterious effects of MF on isometric handgrip endurance tasks (Brown et al., 2017). Three studies in Table 2.1 offered financial incentives as an external motivation to neutralise the negative effects of MF on TT performance (Brown et al., 2018; MacMahon et al., 2014; Pageaux et al., 2014). However, these studies still demonstrated a significant reduction in TT performance following MF intervention. This discrepancy could be attributed to differences in experimental settings, as these studies assessed running (MacMahon et al., 2014; Pageaux et al., 2014) or cycling TT performance (Brown et al., 2018) instead of isometric endurance performance. Similarly, Harris et al. (2021) found that monetary incentives did not lead to significant improvement in 20-minute cycling TT performance following a 12-minute MF protocol. While the involvement of monetary rewards increased the tendency to select a more vigorous intensity over a moderate one during the second half of the cycling TT (Harris et al., 2021), this did not lead to improved TT performance. Specifically, while the monetary incentive may encourage participants to engage in higher-intensity exercise, it does not necessarily improve TT performance and may even add complexity to understanding the effects of MF. Therefore, it is recommended that an investigation into MF avoid using financial incentives to avoid potential confusion. Standardising the experimental setting and motivational aspects would help ensure more reliable and consistent results in research.

Table 2.1 Overview of the laboratory-based MF protocol on time trial performance (n = 18).

Study & Study design	Participant (Characteristics, number, age, training history)	Control condition (CON)	MF induction method (INT)	Subjective ratings of fatigue related variables following mental fatigue protocol (CON vs INT)	Effects of MF on subsequent sport performance (assessment, variables)
Batista et al. (2021) Randomised crossover design	**Orienteers** 15M, Age: 30 ± 8, > 3 years of competition experience	10 min observational task and 20 min relaxation	30 min incongruent Stroop task	Motivational state (0 to 4-point Likert Scale): ~ Motivational state (ES = 0) 0-10 Perceived recovery status: Lower internal load (ES = -0.05)	~ 3.1km Orienteering racetrack (ES = 0.20)
Brown and Bray (2018) Randomised crossover design	**University students** 13M12F, Age: 20.16 ± 1.48, involved in physical activity: 92.13 ± 44.24 min per week	Watching a 50-minute documentary	50 min AX-CPT	↑ MF (VAS) ($p = 0.001$, $d = 0.76$)	30 min self-paced cycling TT: ↓ Total work performed ($p = 0.03$, $\eta^2_p = 0.32$)
Clark et al. (2019) Randomised crossover design	**Untrained** 10M, Age: 25.8 ± 4.6, VO_{2peak}: 39.0 ± 7.3 mL kg^{-1} min^{-1}, Trained < 3 hours/week **Trained** 10M, Age: 27.4 ± 6.3, VO_{2peak}: 58.3 ± 4.1 mL kg^{-1} min^{-1} , Trained > 9.5 hour/week	Watching a 30-minute documentary	30-minute N-back task and a mixture of congruent and incongruent Stroop colour task (alternated on a 2- and 3-min loop)	Positive and negative affect scale: Untrained: ↓ Positive affect ($p = 0.036$) CON: 24.3 ± 4.6; INT:19.9 ± 7.5 ~ Negative affect Trained: ~ Positive affect ↑ Negative affect CON: 12.2 ± 2.7; INT: 15.1 ± 3.7	6 min constant-work-rate: ~ Pulmonary Oxygen uptake 6 min cycling TT: ↑ Power output in both untrained and trained individuals ($p < 0.05$) ~ work completed ($p > 0.05$)
Filipas et al. (2018) Randomised counterbalanced cross-over design	**Youth Rowers** 11M6F, Age: 11 ± 1.06, > 2 training session per week in local club	60-minute drawing task with grey pencil	INT1: 60 min MIST INT2: 60-minute arithmetic test	CON vs INT1 vs IN2: BRUMS: ~ Vigor ($p = 0.151$, $\eta^2_p = 0.117$) ~ Fatigue ($p = 0.102$, $\eta^2_p = 0.15$) NASA-TLX: ↑ Effort ($p < 0.001$, $\eta^2_p = 0.672$; INT1 vs INT2 $p = 0.527$) ↑ Mental demand ($p < 0.001$, $\eta^2_p = 0.585$; INT1 vs INT2 $p =1.00$)	1500m rowing TT: ~ Average power ($p = 0.208$, $\eta^2_p = 0.093$) CON: 121.71 ± 50W; INT1 118.94 ± 49.69W; INT2 118.92 ± 51.89W ~ Average speed ($p = 0.341$, $\eta^2_p = 0.065$) CON: 12.44 ± 1.76 km h^{-1}; INT1 12.35 ± 1.72 km h^{-1}; INT2 12.33 ± 1.77 km h^{-1} ~ Average stroke rate ($p = 0.062$, $\eta^2_p = 0.16$)

				↑ Temporal demand ($p = 0.012$, $\eta^2_p = 0.242$; INT1 vs INT2 $p = 0.922$) ↑ Frustration ($p = 0.004$, $\eta^2_p = 0.358$; INT1 vs INT2 $p = 1.00$) ~ Physical demand ($p = 0.229$, $\eta^2_p = 0.089$) ~ Performance ($p = 0.158$, $\eta^2_p = 0.109$)	CON: 28.65 ± 3.33 rpm; INT1 27.94 ± 2.97 rpm; INT2 28.88 ± 3.28 rpm ~ Completion time ($p = 0.521$, $\eta^2_p = 0.036$) CON: 442 ± 63.97s; INT1 445.29 ± 61.52s; INT2 446 ± 62.30s
Filipas et al. (2019) Randomised counterbalanced crossover design	**Road cyclist** 10M, Age: 20.0 ± 1.2, VO_{2max}: 69.0 ± 4.4 mL min-1 kg-1, peak power output: 380 ± 39W, > 3 years of experience	Watching a 30-minute video	30 MIST	BRUMS: ↑ Fatigue ($p = 0.002$, $\eta^2_p = 0.678$) ↓ Vigor ($p = 0.018$, $\eta^2_p = 0.479$) NASA-TLX: ↑ Effort ($p < 0.001$) ↑ Mental demand ($p < 0.001$) ↑ Temporal demand ($p < 0.001$) ↑ Frustration ($p = 0.001$) ~ Physical demand ($p = 0.56$) ~ Performance ($p = 1.00$)	30 min cycling TT: ~ Power output during TT ($p = 0.234$, $\eta^2_p = 0.129$) ↓ Overall power output ($p = 0.007$, $\eta^2_p = 0.574$) INT: 287 ± 23W; CON: 295 ± 23W ↓ Cadence ($p = 0.043$, $\eta^2_p = 0.382$) INT: 100 ± 7 rpm; CON: 102 ± 6 rpm
Fortes et al. (2020) Randomised cross-over design	**Professional Swimmers** 14M11F, Age: 20.4 ± 2.06, trained 5.8 ± 0.5 sessions/week with 42.5 ± 6.2 km swum/week, 8.4 years of experience in international and national level swimming competition	Watching a 30 min coaching videos	30 min usage of social media application (WhatsApp, Facebook and Instagram) on smartphone	CON vs 50MF, 100MF, 200MF: ↑ MF (VAS) ($p = 0.01$, $\eta^2 = 0.8$) 50MF vs 100MF vs 200MF: ~ MF (VAS) ($p = 0.72$) 50CON vs 100CON: ~ MF (VAS) ($p = 0.36$) 50CON vs 200CON: ~ MF (VAS) ($p = 0.72$) 100CON vs 200CON: ~ MF (VAS) ($p = 0.62$)	CON vs INT 50m Freestyle swim: ~ completion time ($p = 0.81$, $\eta^2 = 0.02$) 100m Freestyle swim: ↑ completion time ($p = 0.01$, $\eta^2 = 0.27$) ↓ speed in last 50m ($p = 0.91$) 200m Freestyle swim: ↑ completion time ($p = 0.01$, $\eta^2 = 0.42$) ↓ speed in second 50m ($p = 0.01$)
Gattoni et al. (2021) RCT	**Amateur long-distance runners** **46M,** Age: 43.8 ± 8.6, VO2 peak 46.0 ± 4.1 ml/kg/min, participated in marathon or half-marathon event	50-minute of reading a magazine	50 min simple response task	NASA-TLX: ↑ Effort ↑ Mental demand ↑ Temporal demand ~ Performance ~ Physical demand ~ Frustration ↑ MF ~ Physical fatigue	~ Half-marathon performance ($p = 0.265$) ~ Running speed ($p = 0.910$)

	during 2015-2017 held by Run4Science			Intrinsic motivation and success motivation scales: ~ Intrinsic motivation ~ Success motivation	
Holgado et al. (2019) Randomised counterbalanced within subject design	**Cyclists** 28M, Age: 27.0 ± 7.4, trained > 6 hour per week	20 min 1-back test during 20 min cycling TT	20 min 2-back test during 20 min cycling TT	↑ MF (VAS)	20 min self-paced cycling TT: ~ average power output
Lam et al. (2021) RCT	**Reactional Runners** Study 2: 7M2F, Age: 21.1 ± 1.2, reactional runners	Study 2: N/A	30 min MIST	100-mm VAS: ↑ MF (d = 1.44) BRUMS: ↑ Fatigue (d = 0.67) ↓ Vigor (d = -0.99)	5km TT: ~ completion time (d = -0.2)
MacMahon et al. (2014) RCT	**Recreational Active** 18M2F, Age: 25.4 ± 3.24, Trained 2.84 ± 1.79 hour/week	6-minute AXCPT & 84-minute documentary	90 min AX-CPT	POMS: ↓ Positive mood (p = 0.049) ↑ Fatigue (p = 0.008)	3000m running TT: ↑ Completion time (p = 0.009)
Martin et al. (2016) Randomised crossover design	**Professional Road Cyclists** 11M, Age: 23.4 ± 6.4, peak power output: 414 ± 48W, trained > 500km/week, > 5 years of cycling experience **Recreational Road Cyclists** 9M, Age: 25.6 ± 5.3, peak power output: 261 ± 28W, trained ~ 80km/week, ~2 years of cycling experience	Sit quietly and focus on a black cross for 10-minute	30 min MIST	Four-Dimensional Mood Scale: No significant main effects of group and condition in positive energy, relaxation, tiredness, negative arousal CON vs INT NASA-TLX: ↑ Effort ($p = 0.033$, $\eta^2_p = 0.24$) ↑ Mental demand ($p < 0.001$, $\eta^2_p = 0.838$) ↑ Temporal demand ($p < 0.001$, $\eta^2_p = 0.887$)	20 min cycling TT: Professional: ~ Average speed ($p = 0.261$, $\eta^2_p = 0.138$) CON: 44.3 ± 1.8 km h^{-1}; INT: 44.1 ± 2.2 km h^{-1} ~ Distance covered ($p = 0.223$, $\eta^2_p = 0.16$) CON: 14.8 ± 0.6 km; INT: 14.8 ± 0.7 km Recreational: ↓ Average speed ($p = 0.003$, $\eta^2_p = 0.683$) CON: 35.5 ± 1.9 km h^{-1}; INT: 34.4 ± 2.6 km h^{-1} ↓ Distance covered ($p = 0.006$, $\eta^2_p = 0.633$) CON: 11.8 ± 0.6 km; INT: 11.4 ± 0.9 km
Pageaux et al.(2014)	**Recreational Active** 8M4F, Age: 21 ± 1, Trained ≥ 2 per week for last 6 months	30-minute congruent Stroop task.	30 min IST	BRUMS: ~ Fatigue (p = 0.888) ↓ Vigor (p = 0.028)	5km Running TT: ↓ Running speed ($p = 0.003$, $\eta^2_p = 0.562$) ↑ Completion time ($p = 0.008$, $\eta^2_p = 0.489$) CON: 23.1 ± 3.8 min; INT: 24.4 ± 4.9 min

Randomised crossover design				NASA-TLX: ↑ Effort ($p = 0.009$, $\eta^2_p = 0.481$) ↑ Mental demand ($p = 0.042$, $\eta^2_p = 0.324$) ~ Temporal demand, Performance, Frustration	NASA-TLX towards TT: ↑ Mental demand ($p = 0.005$) ↓ Performance ($p = 0.044$) ~ Effort, Temporal demand, Frustration
Pageaux et al. (2015) Randomised counterbalanced design	**Recreational Active** 12M, Age: 25 ± 4, Trained ≥ 2 per week for last 6 months	30-minute congruent Stroop task	30 min MIST	BRUMS: ↑ Fatigue ($p = 0.009$) ↓ Vigor ($p = 0.009$) NASA-TLX: ↑ Effort ($p = 0.022$, $d = 0.772$) ↑ Mental demand ($p = 0.012$, $d = 0.861$) ↑ Temporal demand ($p = 0.050$, $d = 0.626$)	6 min cycling: ~ Cadence ($p = 0.919$)
Penna et al. (2018b) Randomised crossover design	**Youth Swimmers** 11M5F, Age: 15.45 ± 0.51; 7.35 ± 2.20 years of experience with average training distance 30,000m/week	Watching a 30-minute emotionally neutral documentary	30 min MIST (paper version)	VAS: ↑ MF ($p < 0.001$, ES = 1.81) ↑ Mental effort ($p < 0.001$, ES = 2.11)	1500m swimming TT: ↑ Completion time by 1.2% ($p < 0.05$, ES = 0.13) ↓ Mean speed ($p < 0.05$, ES = 0.14) INT: 1.155 ± 0.101 m/s; CON: 1.169 ± 0.106 m/s ↓ Pacing for each 300m ($p < 0.05$)
Pires et al. (2018) Randomised counterbalanced design	**Recreational Cyclists** 8M, Age: 29.3 ± 7.9, 5.0 ± 3.2 years of experience	Sit comfortably for 30-minute	30-minute of rapid visual information processing test	Positive and negative affect questionnaire: ↑ Negative affect ($p = 0.03$) ↓ Positive affect ($p = 0.02$) POMS: ↓ Vigor ($p = 0.01$) ↑ Mental confusion ($p = 0.02$) ↑ Tension ($p = 0.03$) ~ Fatigue ($p > 0.05$) ~ Depression ($p > 0.05$) ~ Anger ($p > 0.05$)	20km cycling TT: ↓ Mean power output by 6.5% ($p = 0.03$, $d = 0.98$) CON: 240.2 ± 20.9W; INT: 224.5 ± 17.9W ↑ Completion time by 2.7% ($p = 0.02$, $d = 0.74$) CON: 33.4 ± 1.1 min; INT: 34.3 ± 1.3 min
Roussey et al. (2018) Randomised counterbalanced design	**Competitive cyclists and triathlon** 11M, Age: 27.0 ± 8.6, maximal aerobic power: 346 ± 56W, maximal oxygen uptake 63 ± 5mL.min-1.kg-1	Watching a 60-minute documentary	60 min MIST	BRUMS: ~ Fatigue ($p = 0.768$, $\eta^2_p = 0.002$) ~ Vigor ($p = 0.86$, $\eta^2_p = 0.002$) NASA-TLX: ↑ Effort ($p = 0.002$) ↑ Mental demand ($p < 0.001$)	30 min self-paced cycling at suggested RPE intensity: ~ Mean power output ($p = 0.501$)

Silva-Cavalcante et al. (2018) Randomised counterbalanced order	**Recreational Road Cyclists** 8M, Age: 33.8 ± 7.2, Peak power output: 388 ± 52W, VO_{2max}: 53.6 ± 5.9 mL min^{-1} kg^{-1}, trained ~ 370km/ week, ~ 5 years of experience	Watching a 90-minute documentary	90 min AX-CPT	VAS: ↑ Fatigue ($p = 0.011$, $\eta^2_p = 0.873$) ~ Motivation ($p = 0.667$, $\eta^2_p = 0.066$)	4km cycling TT: ~ Completion time ($p = 0.717$, $d = 0.011$) CON: 376 ± 27s; INT: 376 ± 26s ↓ Performance in first and last 500m ($p < 0.001$, $\eta^2_p = 0.611$) ~ Power output ($p = 0.343$, $\eta^2_p = 0.142$)
Staiano et al. (2018) Randomised crossover design	**U17 National team kayakers** Age: 16.9 ± 0.8, ~ 5 years of experience in kayaking experience with ~ 5 training per week	Sit comfortably for 60-minute	60 min MIST	NASA-TLX: ↑ Physical demand (ES = 0.58) ↑ Mental demand (ES = 1.89) BRUMS: ↑ Confusion (ES = 0.97) ↑ Anger (ES = 0.86) ↑ Depression (ES = 0.85) ↑ Fatigue (ES = 1.01) ↓ Vigor (ES = -0.89)	2000m kayak TT: ↑ Completion time by 5.7% CON: 521 ± 36s; INT: 552 ± 30s ↓ Power output (ES = - 0.53 ± 0.24) ↓ Stroke rate

↑: increased significantly; ↓: reduced significantly; ~ : similar to no significant difference compared to CON; AX-CPT: AX Continuous Performance Test; BRUMS: The Brunel Mood Scale; F: Female; IST: Incongruent Stroop Task; Loughborough Soccer Passing Test: LSPT; Loughborough Soccer Shooting Test: LSST; M: Male; MF: Mental Fatigue; MIST: Modified Incongruent Stroop Task; VAS: 100-mm Visual Analogue Scale; NASA-TLX: NASA Task Load Index; POMS: The Profile of Mood States IST: Incongruent Stroop Task; Small-sided game: SSG; TT: Time-trial: TTE: Time-to-exhaustion; YYIRT1: Yo-Yo Intermittent Running Test Level 1.

2.2.2 Time-to-Exhaustion at a Fixed Intensity

The summary of the discussed literature on the effects of MF on subsequent TTE performance is presented in Table 2.2. According to the evidence in Table 2.2, the impairment in TTE performance under the MF state ranged from 3% (Lopes et al., 2020) to 7.9% (Penna et al., 2018a). Fifteen studies in Table 2.2 reported a significant decline in subsequent TTE performance following an MF protocol (Boat et al., 2020; Boat & Taylor, 2017; Filipas et al., 2020; Lam et al., 2021; Lopes et al., 2020; MacMahon et al., 2019; Marcora et al., 2009; Penna et al., 2018a; Salam et al., 2018; Slimani et al., 2018; Smith et al., 2015; Smith et al., 2016; Veness et al., 2017; Weerakkody et al., 2021; Zering et al., 2017), and these findings were consistent across various athletic populations, regardless of the duration of the MF protocol (Venesss et al., 2017; Smith et al., 2016; Smith et al., 2015; Salam et al., 2018; Penna et al., 2018a; Lopes et al., 2020; Filipas et al., 2020; Weerakkody et al., 2021). This contradicts the conclusion that the trained population present better resistance to MF (Martin et al., 2016), and supports a recent systematic review indicating that performance level does not reduce the likelihood of experiencing MF (Habay et al., 2023).

While all included studies in Table 2.2 demonstrated a significant increase in MF and MF-related ratings following MF protocol, three studies involving untrained and recreationally active individuals reported no significant impairments on TTE performance (Holgado et al., 2020; Martin et al., 2019; Schucker et al., 2016). However, this does not necessarily imply that training status directly influences the effects of MF on TTE performance, as seven studies using untrained to recreationally trained individuals showed significantly impaired TTE performance (Boat et al., 2020; Boat & Taylor, 2017a; Lam et al., 2021; MacMahon et al., 2019; Marcora et al., 2009; Slimani et al., 2018; Zering et al., 2017). The insignificant changes among the untrained population could be attributed to the nature of TTE test. Although the TTE test is a valid and reliable measurement of endurance capacity (Amann et al., 2008), the TTE differs from TT in that individuals must sustain a fixed intensity for as long as possible. This requires a high level of conscious self-regulation, as individuals must balance perceived exertion while maintaining energy output to match the given exercise intensity (Amann et al., 2006). Therefore, the insignificant findings between normal and MF conditions among untrained populations may be due to physiological weaknesses rather than the direct impact of MF. Conversely, the significant early disengagement observed in trained athletes during TTE could be attributed to MF, as it has been shown to increase perceived exertion during exercises (Van Cutsem et al., 2017). These findings highlight the importance of considering both the specific demands of the testing protocol and the performance level of participants when interpreting the effects of MF on endurance performance.

Additionally, there is inconsistency in the type of activity used as the control condition across different studies, which could introduce confounding variables and lead to variations in participants' baseline states. As observed in Table 2.2, control activities varied between studies, including watching a documentary or engaging in a less challenging cognitive task. However, the impact of these control activities remains unknown. Although two studies employed emotionally neutral videos as a control condition (Martin et al., 2019; Holgado et al., 2020), and one study utilised an easier version of the MF protocol (Schucker et al., 2016), it is difficult to determine whether participants perceived these activities as emotionally neutral or less cognitively demanding than the MF condition. This uncertainty arises due to individual differences in task perception.

The absence of a significant impact on subsequent TT performance may be attributed to limitations in the experimental design. Specifically, control activities were not pre-evaluated by participants to ensure they did not influence subsequent performance. Another notable limitation among studies is the variation in transition periods between the completion of the MF protocol and the start of TTE testing. Some studies conducted TTE testing immediately after the MF protocol (Boat & Taylor, 2017a; Boat et al., 2020; Lopes et al., 2020; MacMahon et al., 2019; Penna et al., 2018a; Schucker et al., 2016; Slimani et al., 2018), whereas others allowed for varying transition times, such as 2 minutes (Smith et al., 2016; Zering et al., 2017), 3 minutes (Filipas et al., 2020), 5 minutes (Martin et al., 2019; Veness et al., 2017), 10 minutes (Lam et al., 2021; Smith et al., 2015) and 15 minutes (Marcora et al., 2009; Salam et al., 2018; Holgado et al., 2020). Interestingly, insignificant findings on subsequent TTE performance were observed across studies with both immediate and prolonged transition periods after MF intervention. This suggests that the transition time itself may not be a critical factor in determining the effects of MF on TTE performance, highlighting the need for further research to explore additional methodological variables that could contribute to these discrepancies.

Furthermore, the absence or negative effects of MF were observed not only in TTE cycling and running performance but also in static TTE testing such as the wall-sit test (Boat & Taylor, 2017a; Boat et al., 2020). This indicates that the type of physical measurement may not be directly related to the significance of the findings. Additionally, some studies demonstrated better TTE performance under MF conditions than the control condition (Holgado et al., 2020; Schucker et al., 2016), which contrasts with the majority of the findings in Table 2.2 that indicate MF does not affect TTE performance. Importantly, Martin et al. (2019) was the only study in Table 2.2 that recorded the occupation of the participants and found that participants engaged in cognitively demanding occupations maintained similar endurance performance following the MF intervention. While Habay et al. (2023) concluded that performance level does not affect MF susceptibility, further research into the role of occupation in relation to the impact of MF on TTE performance could help explain the insignificant changes observed in some studies.

Moreover, this chapter aligns with a previous meta-analysis of seven studies, which concluded that MF has a small effect on subsequent TTE performance (d = -0.49, 95%CI -0.66, -0.32) (Grgic et al., 2022). In conclusion, the evidence discussed in this section suggests that MF intervention can impair the TTE performance of trained individuals. However, the effect of MF on the TTE performance of recreationally active or untrained individuals remains conflicting and requires further investigation. Further investigation should explore the role of occupational cognitive demands in mediating the effects of MF on TTE performance to improve the understanding of the relationship between MF and TTE performance.

Table 2.2 Overview of the MF protocol on time-to-exhaustion performance (n = 19).

Study & Study design	Participant (Characteristics, number, age, training history)	Control condition	MF induction method	Subjective ratings of fatigue related variables following mental fatigue protocol	Effects of MF on subsequent sport performance (assessment, variables)
Boat et al. (2020) Counterbalanced design	**Healthy** 11M18F, Age: 20.7 ± 0.8, exercised 3 ± 2 days per week	4-minute congruent Stroop task	4, 8 and 16 min IST	Borg's 10-point scale: ↑ Mental exertion ($p < 0.001$) CON: 0.8 ± 0.1 4 min: 2.5 ± 0.2 8 min: 3.9 ± 0.3 16 min: 5.5 ± 0.4	Wall-sit: ↓ TTE performance ($p < 0.001$) CON: 166 ± 9s 4 min: 148 ± 9s ($p = 0.008$, $d = 0.38$) 8 min: 140 ± 9s ($p = 0.001$, $d = 0.53$) 16 min: 116 ± 8s (p = < 0.001, $d = 1.13$)
Boat and Taylor (2017a) Counterbalanced design	**Healthy** 21M42F, Age: 22 ± 3, trained 4 ± 2 days per week	4-minute congruent Stroop task	4 min MIST	Borg's 10-point scale: ↑ Mental exertion ($p < 0.001$) CON: 1.33 ± 1.17; INT: 5.15 ± 1.83	Wall-sit: ↓ TTE performance ($p = 0.01$) CON: 147.31 ± 73.01s; INT: 130.16 ± 70.01s
Filipas et al. (2020) Randomised counterbalanced design	**Soccer Players** 12 from U14; 12 from U16; 12 from U18; > 3 years of experience in competing at national level	15-minute reading an emotionally neutral online magazine	30 min MIST	100-mm VAS: ↑ MF in U14, U16 and U18 group ($p < 0.001$) NASA-TLX: ↑ Effort, Frustration, Mental demand and Temporal demand in U14, U16 and U18 group ($p < 0.001$)	YYIRT1: ↓ Distance covered in U14, U16 and U18 group ($p < 0.05$)
Holgado et al. (2020) Randomised counterbalanced design	**Reactional Active** 24M6F, Age: 23.5 ± 6.3, Trained > 6 hour per week	Watching a 90-minute documentary	90 min AX-CPT	VAS: ↑ MF ↓ Physical fatigue BRUMS: ↑ Fatigue ↓ Vigor	TTE cycling: ~ Performance CON: 705.4 ± 79.49s; INT: 765.5 ± 92.05s ~ average HR ($BF_{01} = 2.587$) CON: 161 bpm ; INT: 156 bpm
Lam et al. (2021) Randomised crossover design	**Reactional Active** Study 1: 9M, Age: 22 ± 2.6, recreationally active in variety of sport and exercise	Study 1: N/A	30 min MIST	100-mm VAS: ↑ MF ($d = 2.01$) BRUMS: ↑ Fatigue ($d = 2.55$) ↓ Vigor ($d = -1.9$)	YYIRT1: ↓ Distance covered ($d = -0.2$)
Lopes et al. (2020) Randomised controlled crossover design	**Mid- and Long-Distance Runners** 16M, Age: 25 ± 1, $VO_{2\,max}$: 73.24 ± 1.37 mL kg^{-1}	Watching a 45-minute documentary	45 min mixture of congruent and	100mm VAS: ↑ Mental effort ($p < 0.001$, $\eta^2_p = 0.453$) CON (W: 4.1 ± 0.7cm, M: 3.6 ± 0.7cm) INT (W: 6.0 ± 0.7cm, M: 6.2 ± 0.6 cm) ↑ MF ($p = 0.018$, $\eta^2_p = 0.179$)	↓ TTE treadmill running performance: Women: -6 ± 6% Men: -3 ± 5%

	min^{-1}, Weekly training distance: 96 ± 9 km 15W, Age: 25 ± 1, VO_{2max}: 61.29 ± 1.45 mL kg^{-1} min^{-1}, Weekly training distance: 88 ± 7 km		incongruent Stroop task	CON (W: 5.3 ± 0.6cm, M: 4.3 ± 0.6cm) INT (W: 6.8 ± 0.6cm, M: 5.8 ± 0.6 cm) BRUMS: ↑ Fatigue ($p = 0.119$, $\eta^2_p = 0.082$) ↓ Vigor ($p = 0.341$, $\eta^2_p = 0.031$)	
MacMahon et al. (2019) Randomised counterbalanced design	**Active individuals** 10M3F, Age: 19.92 ± 1.75, 10.8 ± 4.48 years of playing experience	30-minute congruent Stroop task	30 min IST	7-point scale: ↑ Cognitive fatigue ($p < 0.01$, $\eta^2_p = 0.651$) CON: 3.31 ± 1.43; INT: 5.31 ± 1.25 ↑ Effort ($p < 0.05$, $\eta^2_p = 0.667$) CON: 2.54 ± 1.56; INT: 4.54 ± 1.27	20m Shuttle run test: ↓ Distance covered ($p < 0.01$, $\eta^2_p = 0.67$) CON: 9:20 ± 2:28 min; INT: 8:48 ± 2.32 min
Marcora, Staiano & Manning (2009) Randomised crossover design	**Recreational Active** 10M6F, Age: 26 ± 3, VO_{2peak}: 52 ±8 ml kg^{-1} min^{-1}	Watching a 90-minute of emotionally neutral documentary	90 min AX-CPT	BRUMS: ↑ Fatigue ($p = 0.005$) ↓ Vigor ($p < 0.001$)	TTE cycling: ↓ Performance ($P = 0.003$) CON: 754 ± 339s; INT: 640 ± 316s ~ Average cadence rate per minute CON: 84 ± 12 RPM; INT: 83 ± 13 RPM
Martin et al. (2019) Randomised crossover design	**Untrained and Recreational Active** 8M15F, Age: 26 ± 6	Watching a 90-minute documentary	90 min MIST	100-mm VAS: ↑ Fatigue ($p < 0.001$, $\eta^2_p = 0.265$) CON: 31 ± 20; INT: 48 ± 22 NASA-TLX: ↑ Effort ($p < 0.001$, $\eta^2_p = 0.889$) ↑ Frustration ($p < 0.001$, $\eta^2_p = 0.686$) ↑ Physical demand ($p = 0.001$, $\eta^2_p = 0.014$) ↑ Mental demand ($p < 0.001$, $\eta^2_p = 0.826$)	TTE cycling: ~ Performance ($p = 0.074$, $d = 0.11$) CON: 628 ± 247s; INT: 601 ± 245s
Penna et al. (2018a) Randomised crossover design	**Regional-level Handball Players** 12M, Age: 17.5 ± 3.6; 5 ± 2.2 years of experience	Watching a 30-minute documentary	30 min MIST (paper version)	100-mm VAS: ↑ MF ($p < 0.01$, ES = 1.32) ↑ Mental effort ($p < 0.001$, ES = 2.8)	YYIRT1: ↓ total distance covered by 7.9 ± 10.4% ($p < 0.05$, ES = 0.4)
Salam, Marcora & Hopker (2018) Randomised crossover design	**Trained Cyclists** 11M, Age: 38 ± 6, > 3 years of experience, VO_{2peak}: 60.5 ± 4.1 ml kg^{-1} min^{-1}	30-minute of reading a magazine	30 min MIST	10-point scale: ↑ MF ($p < 0.01$)	TTE cycling: ↓ performance ($p < 0.01$) 40% VO_{2peak} ($p < 0.05$) CON: 720 ± 180s; INT: 648 ± 171s 60% VO_{2peak} ($p < 0.05$) CON: 422 ± 88s; INT: 341 ± 84s 80% VO_{2peak} ($p < 0.05$) CON: 275 ± 58s; INT: 231 ± 65s 100% VO_{2peak} ($p < 0.05$) CON: 190 ± 38s; INT: 156 ± 38s

					~ Critical power ($p > 0.05$)
Schucker and MacMahon (2016) – Study 1 RCT	**Active individuals** 3M9F, Age: 29.41 ± 14.47, 10 ± 7.35 years in sports	10 min congruent Stroop task	10 min MIST	7-point scale: ↑ Cognitive fatigue ($p = 0.014$, $d = 0.85$) CON: 2.83 ± 1.11; INT: 3.75 ± 1.14 ↑ Level of effort ($p = 0.006$, $d = 1.0$) CON: 3.17 ± 1.40; INT: 4.58 ± 1.08 BRUMS: ~ Fatigue	20m Shuttle run test: ~ TTE performance ($p = 0.60$) CON 9:15 ± 1:28 min; INT 9:09 ± 1:39 min HRmax ($p = 0.54$) CON: 180.3 ± 15.66; INT:178.6 ± 10.97
Schucker and MacMahon (2016) – Study 2 RCT	**Active individuals** 5M9F, Age: 30.64 ± 13.11, 14.54 ± 8.65 years in sports training	Watching a 10-minute video	10 min MIST	7-point scale: ~ Cognitive fatigue ($p = 0.77$) CON: 3.54 ± 1.57; INT: 3.45 ± 1.29 ↑ Level of effort ($p = 0.02$, $d = 0.84$) CON: 3.82 ± 2.14; INT: 5.45 ± 1.51 BRUMS: ~ Fatigue	20m Shuttle run test: ~ TTE performance ($p = 0.84$) CON 8:27 ± 2:01 min; INT 8:29 ± 2:05 min
Slimani et al. (2018) Randomised counterbalanced crossover design	**Active Adolescents** 10M, Age: 16 ± 1.05, high school team sport athletes	30-minute of reading a magazine	30 min MIST (paper version)	BRUMS: ↑ Fatigue ($p < 0.001$, ES = -5.65)	20m shuttle run test: ↓ Distance covered ($p = 0.021$, ES = 1.19)
Smith et al. (2015) Randomised counterbalanced design	**Team Sport Players** 10M, Age: 22 ± 2, VO_{2max}: 48 ± 6 ml kg^{-1} min^{-1}, > 3 years of competition experience	Watching a 90-minute documentary	90 min AX-CPT	BRUMS: ↑ Fatigue ($p < 0.001$) ↓ Vigor ($p = 0.501$)	15 x 3 min intermittent running: ↓ Total distance ($p = 0.02$): CON: 4136 ± 430m; INT: 4072 ± 409m ↓ Low intensity activity distance ($p = 0.037$): CON: 3255 ± 366m; INT: 3164 ± 372m ~ High intensity activity distance ($p = 0.982$) CON: 908 ± 74m; INT: 908 ± 87m ↓ Overall running velocity ($p = 0.022$) ↓ Low intensity activity ($p = 0.037$) CON: 1.54 ± 0.18ms^{-1}; INT: 1.28 ± 0.18ms^{-1} ~ High velocity ($p = 0.892$) CON: 4.01 ± 0.36ms^{-1}; INT: 4.00 ± 0.39ms^{-1} ~ Peak velocity ($p = 0.652$) CON: 4.93 ± 0.35ms^{-1}; INT: 4.86 ± 0.45ms^{-1} ~ High intensity running ($p = 0.092$) ~ Total work ($p = 0.092$) CON: 2332 ± 259 kJ; INT 2294 ± 239 kJ ~ Low intensity work ($p = 0.100$) CON: 1771 ± 212 kJ; INT: 1730 ± 211 kJ

					~ High intensity work (p = 0.780) CON:561 ± 55kJ; INT: 565 ± 65 kJ
Smith et al. (2016) Randomised counterbalanced design for study 1 & 2	**Soccer Players** Study 1 12M, Age: 24 ± 0.4, recreational players Study 2 14M, Age: 19.6 ± 3.5, 13.6 ± 3.2 years of experience plus playing in local league game	30-minute of reading a magazine at a comfortable place	30 min MIST (paper version)	100-mm VAS: ↑ MF ($p < 0.001$) ↑ Mental effort ($p < 0.001$) CON: 23 ± 20; INT: 70 ± 20 ~ Motivation (p = 0.423) CON: 58 ± 27; INT: 56 ± 21	YYIRT1: ↓ Distance covered ($p < 0.001$) CON: 1410 ± 354m; INT: 1203 ± 402m Study 2 LSPT: ↑ Decision-making time LSST: ↓ Shot frequency, Shot speed ~ Shot accuracy
Veness et al. (2017) Randomised crossover design	**Cricket Players** 10M, Age: 21± 8; ≥ 2 years of experience in a professional club	30-minute of reading a magazine	30 min IST	100-mm VAS: ↑ MF ($p < 0.001$, ES = -7.82) CON: 16.6 ± 3.6; INT: 46.6 ± 5.86 ~ Motivation (p = 1.00, ES = -0.02) CON: 82.2 ± 4.4; INT: 82.2 ± 6.3	YYIRT1: ↓ Distance covered (p = 0.023, ES = 0.39) CON: 1892 ± 357m; INT: 1732 ± 402m
Weerakkody et al. (2021) Randomised crossover design	**Amateur Australian footballers** 25M, Age: 23.8 ± 4.6	Watching a 30-minute documentary	30 min IST	N/A	YYIRT1: ↓ Distance covered (p = 0.03, ES = -0.45) CON: 1182.4 ± 537.78m; INT: 1040 ± 492.75m
Zering et al. (2017) Randomised counterbalanced design	**Untrained and Recreational active university students** 7M8F, Age: 19.56 ± 1.69	Watching a 10.5-minute documentary	10.5 min Stop-signal task	Borg's 10-point scale: ↑ Mental exertion ($p < 0.001$, $\eta^2_p = 0.767$) CON: 1.29 ± 1.36; INT: 4.37 ± 1.92	Increment cycling test: ↓ Peak power output (p = 0.003, d = 0.55) CON: 246.03 ± 52.60W; INT: 240.03 ± 53.37W ↓ Peak oxygen uptake (p = 0.042) CON: 43.91 ± 7.76 ml kg^{-1} O_2 min INT: 42.11 ± 7.53 ml kg^{-1} O_2 min ~ Ventilatory threshold (p = 0.217, d = 0.34)

↑: increased significantly; ↓: reduced significantly; ~ : similar to no significant difference compared to CON; AX-CPT: AX Continuous Performance Test; BRUMS: The Brunel Mood Scale; F: Female; IST: Incongruent Stroop Task; Loughborough Soccer Passing Test: LSPT; Loughborough Soccer Shooting Test: LSST; M: Male; MF: Mental Fatigue; MIST: Modified Incongruent Stroop Task; VAS: 100-mm Visual Analogue Scale; NASA-TLX: NASA Task Load Index; POMS: The Profile of Mood States IST: Incongruent Stroop Task; Small-sided game: SSG; TT: Time-trial: TTE: Time-to-exhaustion; YYIRT1: Yo-Yo Intermittent Running Test Level 1.

2.2.3 Anaerobic performance

The influence of MF protocol on subsequent anaerobic performance is summarised in Table 2.3. Seven studies assessed anaerobic performance using maximal voluntary contraction (MVC) tests (Pageaux et al., 2013; Pageaux et al., 2015) and all-out sprinting tests (Fortes et al., 2020; Fortes et al., 2021; Martin et al., 2015; Vrijkotte et al., 2018; Weerakkody et al., 2021). Notably, none of these studies reported significant impairment following MF interventions, aligning with a previous systematic review that concluded MF has minimal to no effect on power, maximal strength and anaerobic performance (Van Cutsem et al., 2017). However, it is essential to consider the potential influence of anaerobic test selection on these results. MVC tests primarily assess maximal strength, while all-out sprinting tests assess the ability of the phosphocreatine system to rapidly resynthesis ATP (Gastin, 2001). These performance measures may be less susceptible to the effects of MF due to the limited involvement of conscious decision-making compared to aerobic performance (Brown et al., 2020; Pageaux & Lepers, 2018; Van Cutsem et al., 2017). Despite the current evidence, further exploration of different measures is needed to provide a better understanding of the effects of MF on anaerobic performance.

Six studies in Table 2.3 reported a significant increase in perceived fatigue and fatigue-related variables following the MF protocol. However, one study did not measure MF ratings following a 30-minute IST (Weerakkody et al., 2021). Despite this, Weerakkody et al. (2021) revealed a trivial effect of MF on subsequent 20m sprint performance among trained individuals. This is in line with the findings of two studies in Table 2.3 that MF had only a trivial to small effect on anaerobic performance (Fortes et al., 2020; Martin et al., 2015). However, it is important to acknowledge potential differences in anaerobic performance measurement methods across different populations. According to Table 2.3, multi-joint anaerobically based exercises were primarily measured among the trained population (Fortes et al., 2020, Fortes et al., 2021; Martin et al., 2015; Vrijkotte et al., 2018; Weerakkody et al., 2021), whereas the anaerobic performance of recreationally active individuals was measured via MVC (Pageaux et al., 2013; Pageaux et al., 2015). This discrepancy in measurement methods may introduce confounding variables, making it challenging to directly compare the effects of MF on anaerobic capacity across different populations. Furthermore, the limited representation of female participants is concerning as only two studies in Table 2.3 recruited female participants (Fortes et al., 2020; Martin et al., 2015). Although Lopes et al. (2020) found no sex difference in the extent of decrements in the TTE test among mentally fatigued professional runners, the underrepresentation of female participants in Table 2.3 disregarded potential gender-specific responses to MF and fatigue. Given that the fatigue perception and stress responses can differ between men and women (Pageaux & Lepers, 2018), it is essential to include a more balanced gender distribution to capture potential gender-related effects on anaerobic performance under MF conditions.

Besides, the methodology of the included studies in Table 2.3 showed inconsistencies in the timing of anaerobic performance measurements. One study assessed anaerobic performance immediately after the MF protocol (Vrijkotte et al., 2018), while three studies conducted measurements 10 minutes later (Fortes et al., 2020; Pageaux et al., 2013; Pageaux et al., 2015). The remaining two studies did not specify the timing of anaerobic measurements as other measurements such as a 2-minute Stroop task, CMJ, and mean propulsive velocity of 40kg half back squat were conducted beforehand (Fortes et al., 2021; Martin et al., 2015; Weerakkody et al., 2021). Although these two studies used randomised treatment conditions, the order of the measurements was not randomised, introducing the possibility of an order effect that may have contributed to the insignificant findings in anaerobic tests. The inconsistency in methodological design complicates the interpretation of outcomes, highlighting the need for further research to consider individual specificity and outcome measures to increase the comparability of the results. However, despite variations in methodological settings such as the timing of anaerobic measurements, the performance levels of participants, and uneven gender representation, the absence of a significant effect of MF on anaerobic performance remains consistently observed across studies. Furthermore, it is important to acknowledge that the negative effect of MF is frequently observed in endurance performance as discussed in sections 2.2.1 and 2.2.2. While MF-induced impairments in aerobic performance are well-documented, these effects could indirectly influence anaerobic performance, particularly in sports requiring a combination of aerobic and anaerobic output. Therefore, the potential impact of MF on anaerobic performance in a sporting context cannot be completely dismissed.

Table 2.3 Overview of the MF protocol on anaerobic performance (n = 7).

Study	Participant (Characteristics, number, age, training history)	Control condition	MF induction method	Subjective ratings of fatigue related variables following mental fatigue protocol	Effects of MF on subsequent sport performance (assessment, variables)
Fortes et al. (2020) Randomised crossover design	**Professional Swimmers** 14M11F, Age: 20.4 ± 2.06, trained 5.8 ± 0.5 sessions/ week with an average of 42.5 ± 6.2km/ week, 8.4 years of experience in international and national level swimming competition	Watching a 30-minute coaching videos	30 min usage of social media application (WhatsApp, Facebook and Instagram) on smartphone	100-mm VAS: ↑ MF ($p = 0.01$, $\eta^2 = 0.8$)	50m Freestyle swim: ~ completion time ($p = 0.81$, $\eta^2 = 0.02$)
Fortes et al. (2021) Randomised crossover design	**Trained Sprinters** **16M,** Age: 21.9 ± 0.9, trained 14 ± 1 hours/ week, 100m performance: 12.17 ± 0.69s, 200m performance: 26.81 ± 1.22s, participated in a national university champion competition in Brazil	Watching a 60-minute coaching videos	60 min usage of social media application (WhatsApp, Facebook and Instagram) on smartphone; and 60 min IST	100-mm VAS: ↑ MF ($p = 0.001$, $\eta^2_p = 0.32$) ~ Motivation ($p = 0.96$, $\eta^2_p = 0.002$)	100m sprint: ~ sprint time ($p = 0.81$) 200m sprint: ~ sprint time ($p = 0.21$) ~ CMJ ($p = 0.55$)
Martin et al. (2015) Randomised crossover design	**Triathletes** 7M5F, Age: 23 ± 3, $VO_{2\,max}$: 53 ± 13.1 ml kg^{-1} min^{-1}, participate high-intensity training ≥ 3 time a week	Watching a 90-minute documentary	90 min AX-CPT	Rating scale of Mental Effort: ↑ Cognitive effort ($p < 0.001$, $d = 1.994$) CON: 26.0 ± 23.1; INT: 71.7 ± 18.7 POMS: ↑ Fatigue ($p = 0.015$, $\eta^2_p = 0.431$) ↓ Vigor ($p < 0.001$, $\eta^2_p = 0.794$)	3 min all-out cycling test: ~ Peak power ($p = 0.412$, $d = 0.246$) CON: 700 ± 301W; INT: 689 ± 298W ~ Mean power ($p = 0.217$, $d = 0.378$) CON: 294 ± 77W; INT: 298 ± 79W ~ Critical power ($p = 0.537$, $d = 0.184$) CON: 242 ± 54W; INT: 238 ± 55W ↓ Cadence (from 45s to 120s; $p < 0.001$) ↓ Power output (from 15s to 75s; $p = 0.001$) ~ Isometric knee extensor strength ~ CMJ
Pageaux et al. 2013 Randomised counterbalanced design	**Recreationally Active** **10M, Age: 22** ± 2	Watching a 90-minute documentary	90 min AX-CPT	BRUMS: ~ Vigour ($p = 0.003$) ↑ Fatigue ($p = 0.007$) 5-point scale: ~ Intrinsic motivation ($p = 1.00$) ~ Success motivation ($p = 0.111$)	MVC torque of knee extensors ~ knee extensors MVC ~ Peak twitch

Pageaux et al. (2015) Randomised counterbalanced design	**Recreational Active** 12M, Age: 25 ± 4, Trained ≥ 2 per week for last 6 months	30-minute congruent Stroop task	30 min MIST	BRUMS: ↑ Fatigue ($p = 0.009$) ↓ Vigor ($p = 0.009$) NASA-TLX: ↑ Effort ($p = 0.022$) ↑ Mental demand ($p = 0.012$) ↑ Temporal demand ($p = 0.050$)	Electromyogram amplitude: ↑ Vastus lateralis activation ($p = 0.046$) ~ Rectus femoris activation ($p = 0.610$) Maximal voluntary contraction torque: ~ Knee extensors ($p = 0.194$)
Vrijkotte et al. (2018) Randomised placebo-controlled crossover design	**Cyclists** 9M, Age: 26 ± 6, VO_{2max}: 61.67 ± 5.05 $ml^{-1}\ kg^{-1}\ min^{-1}$	90-minute rest	90 min IST	100-mm VAS: ↑ MF ($p = 0.04$) POMS: ↑ Fatigue ($p < 0.01$) ↑ Tension ($p = 0.03$) ~ Depression ($p = 0.14$) ~ Anger ($p > 0.05$) ~ Vigor ($p = 0.11$)	2 x Maximal cycling test: ~ Maximum wattage ($p = 0.59$) CON: 360 ± 47W; INT: 360 ± 49W
Weerakkody et al. (2021) Randomised crossover design	**Amateur Australian footballers** 25M, Age: 23.8 ± 4.6, community-level Asutralian footballers competing in metropolitan or regional Victorian league	Watching a 30-minute documentary	30 min IST	5-point Likert scale: ~ Motivation ($p = 0.59$)	~ 20m sprint ($p = 0.38$, ES = -0.05) CON: 3.22 ± 0.3s; INT: 3.23 ± 0.15s

↑: increased significantly; ↓: reduced significantly; ~ : similar to no significant difference compared to CON; AX-CPT: AX Continuous Performance Test; BRUMS: The Brunel Mood Scale; F: Female; IST: Incongruent Stroop Task; Loughborough Soccer Passing Test: LSPT; Loughborough Soccer Shooting Test: LSST; M: Male; MF: Mental Fatigue; MIST: Modified Incongruent Stroop Task; VAS: 100-mm Visual Analogue Scale; NASA-TLX: NASA Task Load Index; POMS: The Profile of Mood States IST: Incongruent Stroop Task; Small-sided game: SSG; TT: Time-trial: TTE: Time-to-exhaustion; YYIRT1: Yo-Yo Intermittent Running Test Level 1.

2.2.4 Cognitive performance

Growing evidence demonstrates that MF is detrimental to cognitive performance, influencing decision-making, tactical behaviours, reaction time and response accuracy rather than impairing endurance performance only, as presented in Table 2.4. Most of the performance assessments in the studies included in Table 2.4 were aligned with the characteristics of the individuals except for one study that assessed the golf putting experience of recreationally active individuals (Graham et al., 2017; Shin et al, 2019; Verschueren et al., 2020). Seventeen studies in Table 2.4 demonstrated impaired cognitive performance following MF interventions, including poorer execution of tactical behaviours, slower reaction times and reduced response accuracy. These negative effects were consistent across various sports such as soccer, basketball, table tennis and badminton.

Table 2.4 summarises the overall effects of MF on cognitive performance, with six studies reporting no significant impairment (Campos et al., 2019; Ciocca et al., 2022; Filipas et al., 2020; Kosack et al., 2020; Silva et al., 2023; Vogt et al., 2018). An interesting observation was found in Ciocca et al. (2022), where 10 national under-18 soccer players demonstrated a moderate increase in the total number of passes and successful passes during a 5 vs 5 SSG under a mentally fatigued state. A previous meta-analysis conducted by Clemente et al. (2021), which analysed the physical and tactical performance of U21 youth soccer players during subsequent SSG under MF state, found an unclear to trivial effect on total running distance ($p = 0.307$, ES = 0.13) and a moderate impairment in tactical behaviour ($p = 0.079$, ES = 0.56) including pass decision-making accuracy and attacking behaviour. However, it is important to acknowledge that the ES in this meta-analysis was only based on six studies, limiting its representativeness and generalisability.

Moreover, Filipas et al. (2020) demonstrated that U18 soccer players performed poorly in the LSPT following a 30-minute MIST compared to U14 and U16 soccer players. However, the LSST results remained similar between the control and intervention groups. Other studies in Table 2.4 involving youth soccer players aged 13 to 19 years old, showed a small to moderate impairment in LSST (Smith et al., 2016), LSPT (Smith et al., 2016; Smith et al., 2017) and tactical behaviour in both attack and defence during SSG (Ciocca et al., 2022; Badin et al., 2016; Coutinho et al., 2017; Coutinho et al., 2018). A similar negative effect of MF was also observed in youth basketball SSG, where trained youth basketball players (age: 15 ± 1.2) presented a moderate increase in total turnovers (ES = 0.71), along with trivial and unclear changes in player efficiency (ES = -0.18) following MF intervention (Moreira et al., 2018). Conversely, Vogt et al. (2018) found no effect of MF on the speed of action and ball control in 33 youth soccer players (age: 13.5 ± 1.0) following a 20-minute MF protocol. However, it is important to consider that this study utilised a combination of a 10-minute IST and 10-minute determination task, which differed from the methodological setting used in most studies presented in Table 2.4. The repeated use of MF protocols during the session may have shifted the participants' attention and reduced the effectiveness of MF induction. A detailed discussion on the effectiveness of MF protocol will be discussed in section 2.4.1. The evidence above suggests that younger individuals could experience varying degrees of negative effects from MF and that age may not correlate with resilience to MF. The presence of MF can impair tactical performance, particurarly in tasks that require continuous conscious decision-making such as SSG.

Table 2.4 provides evidence that MF significantly affects cognitive performance, including ball control, successful tackle rate, and tactical behaviour such as accuracy and reaction time in decision-making. Soccer players showed delayed decision-making time but maintained steady passing and shooting accuracy in the Loughborough soccer passing and shooting test (Gantois et al., 2019; Smith et al., 2016; Smith et al., 2017). This delayed decision-making time supports the speed-accuracy trade-off theory, suggesting that the CNS increases decision-making duration as compensation to minimise errors in performance (Rozand et al., 2015). Silva et al. (2023) found that youth soccer players modified their tactical behaviour in both offensive and defensive actions under the influence of MF. However, this study lacked a control activity for comparison and only assessed performance before and after the MF intervention. Additionally, Ciocca et al. (2022) demonstrated no significant effects of MF on subsequent SSG performance following a 30-minute video-based tactical task. While these findings suggest MF may not necessarily impair cognitive performance (Ciocca et al., 2022; Silva et al., 2023), it is crucial for future research to consider the potential impact of elevated MF and mental effort ratings on performance, as increased ratings are believed to negatively affect sports performance (Van Cutsem et al., 2017; Giboin et al., 2019; Brown et al., 2018; Habay et al., 2021).

Importantly, the format of SSG and pitch dimensions differed across studies in soccer-related research in Table 2.4. Some studies included goalkeepers (Coutinho et al., 2017; Coutinho et al., 2018; Kunrath et al., 2018; Kunrath et al., 2020), while others did not (Badin et al., 2016; Ciocca et al., 2022; Trecroci et al., 2020). A similar limitation was also observed in Moreira et al. (2018), where MF reduced overall basketball performance and increased the total number of turnovers in basketball SSG. However, it is important to acknowledge that this study was an RCT instead of a counterbalanced design, meaning that the SSG composition may have led to a mismatch between mentally fatigued and mentally fresh individuals. These methodological variations could affect the cognitive and physical load on participants, potentially contributing to inconsistencies in the results.

Another factor contributing to the insignificant findings following the MF protocol may be that the performance assessment did not appropriately reflect the cognitive demand of the sport. It is important to note that the special judo fitness test employed by Campos et al. (2019) required individuals to perform specific judo throw as many as possible within a given time. While these specific judo throws may involve some cognitive processing, their cognitive demands may be comparatively lesser than other studies in Table 2.4. During the special judo fitness test, the two judokas being thrown remain stationary unlike SSG, where unpredicted movement from opponents and greater cognitive engagement were involved. Similarly, the decision-making performance of soccer players following the MF protocol in Gantois et al. (2019) was assessed in an actual soccer match (2 x 45 min), whereas other studies in Table 2.4 used soccer-specific skill tests (Badin et al., 2016; Ciocca et al., 2022; Coutinho et al., 2017; Coutinho et al., 2018; Filipas et al., 2020; Kunrath et al., 2020a; Silva et al., 2023; Smith et al., 2016; Smith et al., 2017; Trecroci et al., 2020). The duration, physical and cognitive demand of the actual match differ from those of skill-based assessments used in other studies. Despite these discrepancies, a significant impairment in passing decision-making was found during the soccer match, even though the number of passes remained unaffected (Gantois et al., 2019). This finding indicates that MF can still negatively affect cognitive performances in mentally fatigued individuals. Despite variations in experimental settings, the negative effects of MF on tactical and decision-making performance remain evident following the MF interventions. This conclusion aligns with a recent review of the effects of MF on sport-specific motor performance, which supports the notion that MF-induced impairments can be explained by the psychological model and attention resources (Yuan et al., 2023).

Additionally, previous investigations with elite individual and team sports support personnel suggest that both staff and athletes perceive that the presence of MF can reduce awareness and increase decision-making errors (Russell et al., 2019). This further reinforces the discussion above, even though the studies presented in Table 2.4 did not cover all sports. The perceptions of elite sports support personnel (Russell et al., 2019), along with observed impairments in decision-making performance across various sports, provide valuable insights indicating that MF can negatively impact cognitive performance. However, the impact of MF on officiating performance remains inconclusive due to conflicting findings in existing research. Previous research demonstrates that executive functions including reaction time and decision-making ability are unaffected by MF in regional- to national-level football referees (De Lima et al., 2025) and rugby officials (Emmonds et al., 2015). Conversely, other research indicates that decision-making accuracy declines towards the end of a match (Mallo et al., 2012) and following high-intensity physical exertion (Schmidt et al., 2019). Interestingly, some studies have also shown that cognitive performance including reaction time and decision-making ability can improve after vigorous physical activity (Garcia et al., 2024) and competitive football matches (Ahmed et al., 2020; Senecal et al., 2021). Additionally, experienced football referees appear to develop coping mechanisms that enable them to manage both physical and psychological stress, allowing them to maintain decision-making performance throughout matches (Pizzera et al., 2022).

It is important to note that these studies primarily assessed cognitive performance using standardised laboratory-based tasks such as the Stroop task, Go/No-Go task, visuomotor task, and psychomotor vigilance task (De Lima et al., 2025; Schmidt et al., 2019; Senecal et al., 2021; Ahmed et al., 2020; Garcia et al., 2024). Consequently, it remains unclear whether these findings directly translate to sport-specific decision-making, particularly in the context of officiating accuracy under real match conditions. Given the contradictory evidence and the limited research specifically examining the effects of MF on the cognitive performance of officials, further investigation is necessary to draw definitive conclusions.

In summary, MF has a detrimental carryover effect on subsequent sports performance, affecting not only aerobic capacity but also cognitive performance. The deleterious effects of MF are observed in cognitive performance, particularly in reaction time. While individuals may compensate to maintain high decision-making accuracy, their overall cognitive performance and decision-making efficiency remain impaired compared to a non-mentally fatigued state.

Table 2.4 Overview of the MF protocol on cognitive performance (n = 23).

Study	Participant (Characteristics, number, age, training history)	Control condition	MF induction method	Subjective ratings of fatigue related variables following mental fatigue protocol	Effects of MF on subsequent sport performance (assessment, variables)
Badin et al. (2016) Randomised crossover design	**Soccer Players** 20M, Age: 17.8 ± 1.0; 8.3 ± 1.4 year of experience in competition	Watching a 30-minute documentary	30 min mixture of congruent and incongruent Stroop task	100-mm VAS: ↑ MF (ES = 0.73) ↑ Mental effort (ES = 1.34)	15 min SSG (5v5): ↑ Standing/ Walking during game (ES = 0.10) INT: 593 ± 55m CON: 588 ± 56m ↑ Repeated sprint (ES = 0.43) INT: 9.4 ± 4.7 times CON: 8.5 ± 7.0 times ↓ Pass accuracy (ES = -0.25) INT: 81 ± 7 CON: 83 ± 8 ↑ Control error (ES = 0.61) INT: 3.7 ± 1.9 CON: 2.5 ± 1.8 ↓ Tackle success (ES = -0.76) CON: 54 ± 21% INT: 39 ± 15%
Boat et al. (2021a) Randomised counterbalanced crossover design	**Hockey players** 13M, Age 20 ± 1, competing in national or regional leagues	4 min Congruent Stroop task	4 min IST	POMS: ~ Fatigue Borg CR-10 Scale: ↑ Mental exertion (p = 0.005, d = 1.0)	Hockey skill test performance: ~ Total performance time (p = 0.566) ~ Decision-making time (p = 0.301) ↑ Overall errors made (p = 0.014, η^2_p = 0.405) while more error was made in the latter stage of the test, set 3 (p = 0.011) and set 4 (p = 0.017)
Campos et al. (2019) Randomised counterbalanced design	**Judo Players** 9M4W, Age: 19.5 ± 3.0, 7.2 ± 3.9 years of experience	Watching a 30-minute documentary	30 min MIST (paper version)	100-mm VAS: ↑ MF (p = 0.01, ES = 1.11) ↑ Mental effort (p < 0.05, ES = 1.9)	Special Judo Fitness Test: ~ Number of throws (p = 0.86, ES = 0.1) INT: 25.8 ± 1.9 CON: 25.6 ± 2.0 ~ Performance index (p = 0.60, ES = 0.39) INT: 10.9 ± 3.4 CON: 11.9 ± 1.0
Ciocca et al. (2022)	**National U18 Soccer Players** 10 players, Age: 17.2 ± 0.9	Watching a 30-minute documentary	30 min video-based tactical task	100-mm VAS: ↑ Mental effort (p = 0.002, ES = 2.09)	2x7 min 5 vs 5 SSG: ↑ Total passes (p = 0.003, d = 0.72) ↑ Successful passes (p = 0.003, d = 0.82) ~ Passing accuracy (p = 0.055, d = 0.95)

Randomised counterbalanced crossover design					~ Total tackles (p = 0.588, d = 0.28) ~ Total shots (p = 0.671, d = 0.1) ~ Shooting accuracy (p = 0.249, d = 0.5)
Coutinho et al. (2017) Randomised counterbalanced crossover design	**Youth Soccer Players** 12M, Age: 15.9 ± 0.8, 8.9 ± 2.4 years of experience in soccer	20 min light aerobic exercise	20 min whole-body coordination task	100-mm VAS: ↑ MF (p = 0.001, ES = 3.2)	24 min SSG (6v6): ↓ Sprinting ↓ Technical Performance ↓ Linear Synchronization
Coutinho et al. (2018) Randomised counterbalanced design	**Soccer Players** 10M, Age: 13.7 ± 0.5, 6.1 ± 0.9 years of experience, from Portugal regional soccer academy	N/A	30 min MIST	100-mm VAS: ↑ MF (ES = 1)	SSG Performance: ↓ 8% time spent synchronised in the longitudinal displacement ↓ 2% team stretch index ↓ distance between dyads
Faro et al. (2022) Randomised counterbalanced design	**National Basketball Players** 14M, Age: 24.3 +4.1, 6.5 + 1.9 years competitive experience in second division of National Leage of Brazil	Watching 60 min documentary	60 min basketball-based video game on PlayStation 4	100-mm VAS: ↑ MF (p = 0.001, η^2_p = 0.41) ~ Motivation (p = 0.46, η^2_p = 0.002)	Visuomotor task with ball: ↓ Accuracy (p = 0.001, η^2_p = 0.09) ↑ Response time (p = 0.001, η^2_p = 0.17) Visuomotor task without ball: ↓ Accuracy (p = 0.01, η^2_p = 0.08) ↑ Response time (p = 0.01, η^2_p = 0.12)
Filipas et al. (2020) Randomised counterbalanced design	**Soccer Players** 12 from U14; 12 from U16; 12 from U18; > 3 years of experience in competing at national level	15-minute reading an emotionally neutral online magazine	30 min MIST	NASA-TLX: ↑ Effort ↑ Mental demand ↑ Temporal demand	LSPT scores: ↓ U18 ~ U14 & U16 LSST scores (U14, U16 & U18) ~ Shot accuracy ~ Shot speed ~ Shot sequence time
Fortes et al. (2021) Randomised crossover design	**Regional to national level boxers** 13M8F, Age: 23.33 ± 3.46, 8.9 years of experience in national and regional tournaments	Watching a 30 min coaching videos	30 min usage of social media application (WhatsApp, Facebook and Instagram) OR 30 min playing video games	VAS: ↑ MF (p = 0.001, η^2_p = 0.08)	Boxing decision-making performance: ↓ Overall attack decision-making following either social media (p = 0.001) or video games (p = 0.001) ↓ Overall defence decision-making following either social media (p = 0.001) or video games (p = 0.001)
Gantois et al. (2019)	**Professional Soccer Players**	Watching a 30-minute advertising video	15- and 30-minute IST	/	2 x 45 min soccer game: ~ number of passes (p = 0.56) 30 min IST

Randomised counterbalanced crossover design	20M, Age: 22.6 ± 3.3, ≥ 3 years of professional soccer training experiences				↓ Passing decision-making performance [vs 15-min IST ($p = 0.02$); vs CON ($p = 0.05$)] 15-min IST vs CON: ~ Passing decision-making performance ($p > 0.05$)
Head et al. (2017) Randomised counterbalanced design	**Soldiers** 20M, extensive training in rifle marksmanship	Watching a 49-minute documentary	49 min Sustained attention to response task	Subjective workload: ↑ Mental workload ($p < 0.001$)	Marksmanship task: ~ accuracy for hit proportion ($p = 0.57$) ~ Distance of the center of the shot group ($p = 0.34$) ~ Shot group precision ($p = 0.86$) ↑ Errors of commission ($p = 0.001$) ~ Errors of omission ($p = 0.51$) ~ Response time ($p = 0.81$)
Kosack et al. (2020) Randomised crossover design	**Elite Badminton Players** 19M, Age: 20 ± 2.8; 12.5 ± 3.5 years of experience with top 100 national Danish ranking	Watching a 60-minute documentary	60 min MIST	100-mm VAS: ~ Focus ~ Motivation ↑ Fatigue ($p = 0.002$)	Badminton-specific test: ~ Performance ($p = 0.99$) ~ CMJ ($p = 0.59$)
Kunrath et al. (2020a) Non-randomised controlled design	**Soccer Players** 18M, Age: 21.8 ± 2.5, participated in national and state league tournaments	Watching a 30 min documentary	30 min MIST	100-mm VAS: ↑ Perception of MF ($p < 0.001$, $d = 2.764$)	12 min SSG (4v4): ↑ Total distance covered ($p = 0.008$, $d = 0.396$) ↑ Average speed ($p = 0.027$, $d = 0.38$) ↑ Jogging distance ($p = 0.001$, $d = 0.669$) ↓ Walking distance ($p = 0.027$, $d = 0.702$) ↓ Total accuracy of offensive ($p < 0.001$, $d = 2.34$) and defensive tactical behavior ($p < 0.001$, $d = 2.98$)
Le Mansec et al. (2018) Randomised partial-crossover design	**National Table Tennis Players** 22M, Age: 26.9 ± 8.9, competing at regional to national level	Watching a 90-minute movie	90-minute AX-CPT	100-mm VAS: ↑ Fatigue ($p = 0.001$, $\eta^2_p = 0.431$) NASA-TLX: ↑ Effort ($p < 0.001$, $\eta^2_p = 0.754$) ↑ Mental demand ($p < 0.001$, $\eta^2_p = 0.622$) ↑ Temporal demand ($p < 0.0001$, $\eta^2_p = 0.35$)	Table tennis performance test: ↓ Ball speed ($p = 0.035$) ↓ Accuracy ($p = 0.057$) ↓ Total score ($p = 0.015$) ↑ Number of faults ($p = 0.014$)

Moreira et al. (2018) Randomised controlled trial	**Basketball Players** 32M, Age: 15.2 ± 1.2, compete in major state championship in Brazil	Focusing on the centred black cross in front of the computer screen for 10 min and relaxing for 20 min	30-minute MIST	/	4 x 2.5 min SSG (4v4): ~ Player efficiency – calculation based on points, assists, steals, blocks, rebounds, missed field goals and turnovers (ES = -0.18) ↑ Total turnovers (ES = 0.71)
Shin et al. (2019) RCT	**College Students** 51W, Age: 22.25 ± 1.78; no experience in golf putting	Performing a 3 min neutral transcription and browsing shopping magazines for 7 min	Performing a 3 min neutral transcription and performing a 7 min transcription task with the omission of the letter 'e' and 't'	4-point Likert scale: ↑ MF ($p < 0.001$, $d = 1.81$)	Golf putting performance ↑ Mean radial error ($p < 0.001$)
Silva et al. (2023)	**U17 Soccer Players** 18M, Age: 17.1 ± 0.5, 8.1 ± 1.9 years of practice of football	N/A	30 min IST	100-mm VAS: ↑ MF	The System of Tactical Assessment in Soccer: ~ General offensive performance ($p = 0.485$) ↑ General defensive performance ($p < 0.001$)
Smith et al. (2016) Randomised counterbalanced design	**Soccer Players** Study 2 14M, Age: 19.6 ± 3.5, 13.6 ± 3.2 years of experience plus playing in local league game	30-minute of reading a magazine at a comfortable place	30 min MIST (paper version)	VAS: ↑ MF ($p = 0.016$) ↑ Mental effort ($p < 0.001$)	LSPT: ↑ Penalty time ($p = 0.061$, ES = 0.76) ~ Performance time ($p = 0.061$, ES = 0.55) LSST: ↓ Points per shot ($p = 0.006$, ES = 0.75) ↓ Shot speed ($p = 0.024$, ES = 0.75) ~ Shot accuracy ($p = 0.419$)
Smith et al. (2017) Randomised counterbalanced crossover design	**Soccer Players** 14M, Age: 19.6 ± 3.5; 13.6 ± 3.2 years of soccer experience	30-minute reading a magazine	30 min MIST (paper version)	100-mm VAS: ↑ MF ($d = 0.81$) ↑ Mental effort ($d = 2.47$)	LSPT: ↑ Error ($p = 0.01$, $\eta^2_p = 0.39$) ↑ Missed target ($p = 0.02$, $\eta^2_p = 0.34$) ↓ Perfect passes ($p = 0.04$, $\eta^2_p = 0.28$)
Trecroci et al. (2020) Randomised counterbalanced crossover design	**Soccer Players** 9M, Age: 17.6 ± 0.5; ≥ 4 training sessions per week	Watching a 30-minute documentary	30 min IST on smartphone	100-mm VAS: ↑ MF ($p = 0.001$, ES = 1.88)	2 x 7 min SSG (5v5): ↓ Number of accelerations (ES = -0.71) ↓ The sum of acceleration and decelerations (ES = -0.64) ↓ Passing accuracy (ES = -0.49) ↓ Shot accuracy (ES = 0.01) Decision-making performance: ↓ Passes accuracy (ES = -0.53) ↓ Dribbling accuracy (ES = -0.69)

Van Cutsem et al. (2019) Randomised crossover design	**Healthy individuals** 5M6F, Age: 25 ± 4; not engaged in any kind of regular physical activity for last 5 years **Badminton player** 5M4F, Age: 23 ± 3; ≥8 years badminton experience	Watching a 90-minute documentary	90 min MIST	100-mm VAS: ↑ MF ($p < 0.001$; $\eta^2_p = 0.24$) NASA-TLX: ↑ Effort ↑ Mental demand ↑ Temporal demand	Visuomotor task: Healthy and Badminton players: ~ Response accuracy ↑ Reaction time ($p < 0.001$)
Vogt et al. (2018) RCT	**Soccer Players** 33M, Age: 13.5 ± 1.0; 10.0 ± 1.4 years of experience in soccer competing at the highest regional or national youth level	20 min watching football highlights, reading a magazine or talking to other participants	10 min IST and 10 min determination test	↑ MF (VAS)	Footbonaut ball control task: ~ Speed of action ($p = 0.88$) ~ Ball control ($p = 0.85$)
Weerakkody et al. (2021) Randomised crossover design	**Amateur Australian footballers** 25M, Age: 23.8 ± 4.6	Watching a 30-minute documentary	30 min IST	N/A	↓ Brad Johnson kicking test ($p = 0.048$, $d = -0.4$) ~ AFL agility ($p = 0.51$, $d = -0.13$) ~ Matthew Lloyd clean hands test ($p = 0.66$, $d = 0.10$)

↑: increased significantly; ↓: reduced significantly; ~ : similar to no significant difference compared to CON; AX-CPT: AX Continuous Performance Test; BRUMS: The Brunel Mood Scale; F: Female; IST: Incongruent Stroop Task; Loughborough Soccer Passing Test: LSPT; Loughborough Soccer Shooting Test: LSST; M: Male; MF: Mental Fatigue; MIST: Modified Incongruent Stroop Task; VAS: 100-mm Visual Analogue Scale; NASA-TLX: NASA Task Load Index; POMS: The Profile of Mood States IST: Incongruent Stroop Task; Small-sided game: SSG; TT: Time-trial: TTE: Time-to-exhaustion; YYIRT1: Yo-Yo Intermittent Running Test Level 1.

2.2.5 Applied Sport Performance

Apart from the physical and cognitive performance discussed in sections 2.2.1 to 2.2.4, some research has explored MF in applied sports settings. It is important to note that these applied studies did not implement any MF interventions but instead adopted an observational approach. This section will primarily discuss the effects of MF on psychological responses and the fluctuations in MF as observed in these applied studies.

Perceived MF has been shown to acutely increase following a soccer match, with ratings remaining elevated 24 hours post-match among youth English academy soccer players (Thompson et al., 2020). Similar findings have been observed among Premier League soccer players, where increased MF ratings were reported immediately after the match, as well as one- and two-days post-match (Abbott et al., 2020). A comparable observation was reported in elite netballers, with an acute increase in perceived MF following a netball match (Russell et al., 2019). Furthermore, a longitudinal study over two competitive seasons with elite netballers found that changes in perceived MF differed from other psychological responses such as PF, tiredness, stress, and mood (Russell et al., 2022). Importantly, perceived MF fluctuated significantly during the season, especially in the middle of the competitive period.

While it may seem that MF is primarily induced during competition, previous research indicates that perceived MF is not limited to competition and can also be induced during training (Russell et al., 2021). Interestingly, perceived MF has been reported to be higher during competition preparation and training camps than during the competition periods (Russell et al., 2021). Additionally, cumulative MF has been observed in elite netball pre-season training, with a significant increase in perceived MF reported between weeks 1 and 12, as well as between weeks 14 and 15 (Russell et al., 2022). Although MF ratings fluctuated throughout the training period, the significant increase in MF during the later phases of pre-season training suggests that MF can accumulate over time.

Additionally, Coyne et al. (2021) investigated the effect of MF on ratings of perceived exertion (RPE) among both open and closed skill Olympians during the preparation for the Olympic games. This study reported a trivial correlation between perceived MF and session RPE among Olympians. However, when considering the cumulative effect of MF over a training week, perceived MF had a significant moderate effect ($p < 0.001$, Cohen's $f^2 = 0.265$) on total session

RPE (Coyne et al., 2021). This finding is in line with previous research indicating a delayed recovery in perceived MF and highlights that perceived MF may have a cumulative effect that could affect the internal training load of the athletes. Similarly, Abbott et al. (2022) compared perceived MF and well-being between Premier League goalkeepers and substitute goalkeepers, showing that primary goalkeepers reported higher ratings of perceived MF than substitute goalkeepers. This supports the idea that soccer matches elicit greater MF than the regular training performed by substitute goalkeepers. Furthermore, Russell et al. (2019) found no significant relationship between MF and performance variables such as turnover shooting accuracy during elite netball matches, reinforcing the findings reported in section 2.2.4. However, this does not completely rule out the potential effect of MF on applied sports performance, as the study measured only shooting accuracy and did not assess reaction time. As mentioned in section 2.2.4, MF affects the efficiency of decision-making performance, while mentally fatigued individuals may still maintain accuracy in their decisions. This unaffected performance could be related to the speed-accuracy trade-off theory (Rozand et al., 2015). Since the speed of decision-making was not assessed in the study, it remains inconclusive whether sport-induced MF impacts such performance.

Although not all applied studies have examined performance variables to explain the effects of MF, it is important to note that the work discussed in this section investigated MF within ecological competition and training settings. The evidence shows that athletes can naturally experience MF during sports, with recovery from the elevated MF ratings taking at least 48 hours. Additionally, perceived MF has been shown to accumulate during pre-season and competition preparation periods (Russell et al., 2022; Coyne et al., 2021), potentially impacting RPE and internal training load, which may have implications for the design of training programs. The observed differences in changes between perceived MF and other psychological responses highlight the necessity of investigating perceived MF in applied sports settings to enhance understanding of its effects.

The applied studies discussed above predominantly adopt the definition of MF derived from laboratory-based research, wherein MF is induced through prolonged cognitively demanding tasks, impairing both physical and psychological performance (Coyne et al., 2021; Abbott et al., 2018, Abbott et al., 2022). While some applied research involving elite athletes and practitioners has attempted to address the ecological validity of these laboratory protocols by refining the definition and interpretation of MF based on the perception of the elite population

(Thompson et al., 2020; Russell et al., 2019), deficiencies in understanding MF within real-world sports settings persist. Previous research highlights the limitations of existing research approaches in capturing the natural occurrence of MF in real-world sports environments, which limits our understanding of its impact and practical implications for athletic performance (Roelands et al., 2021). These findings highlight the need for further investigation to bridge the gaps in applied MF research and enhance its relevance to sporting environments.

2.3 The Potential Mechanism of Mental Fatigue

Mentally fatigued individuals often reported elevated perceived exertion and increased negative mood responses following cognitively demanding tasks (Brown et al., 2020; Habay et al., 2021; Van Cutsem et al., 2017). The existing theory proposed by Martin et al. (2018) indicates that MF is associated with the accumulation of adenosine and the inhibition of dopamine in the brain. This theory suggests that engaging in prolonged cognitively demanding tasks increases adenosine levels in the ACC, leading to dopamine inhibition and an increased perception of effort (Smith et al., 2018; Martin et al., 2018). Consequently, this process reduces motivation and induces MF (Smith et al., 2018; Martin et al., 2018). As discussed in section 2.2, MF negatively affects decision-making performance and endurance performance, especially the tasks requiring cognitive control, such as maintaining an optimal pacing strategy during endurance tasks. The accumulation of adenosine is proposed to affect effort-related decision-making behaviour, which may explain why mentally fatigued individuals often present abnormal pacing strategies and an elevated perception of effort compared to the control conditions (Fortes et al., 2020; Silva et al., 2018; Penna et al., 2018b). This reflects how MF negatively affects high-level self-regulation abilities, particularly in maintaining optimal pacing during TT (Konings et al., 2018). Grillon et al. (2015) highlighted that MF can interrupt emotion regulation and suppress positive emotions, resulting in difficulties in controlling actions that require mental effort. Neurotransmitters such as dopamine and serotonin are suggested to be affected when adenosine concentrations in the brain increase following prolonged MF protocol (Martin et al., 2018). These neurotransmitters are particularly sensitive to negative stimuli and contribute to the increased perceived exertion during exercise (Schiphof-Godart et al., 2018, Meeusen et al., 2017; Meeusen et al., 2020). This supports the idea that reduced TT performance is related to increased perceived exertion, higher subjective ratings of MF, and potentially decreased positive mood states in mentally fatigued individuals.

The MF protocol has been shown to impact theta and alpha brain wave activity in the frontal brain regions (Tran et al., 2020), affecting both brain activation and neurotransmitter concentrations (Brownsberger et al., 2013; Schiphof-Godart et al., 2018). These alterations in neurotransmitter activity may influence overall brain function and interactions between neurotransmitters, potentially contributing to the development of MF (Meeusen et al., 2020). While previous research has reported that seven days of phosphocreatine supplementation can reduce the negative effects of MF on cognitive performance (Van Cutsem et al., 2020), it remained inconclusive whether MF-induced impairments can be effectively counteracted by oral supplementation alone. Additionally, interpreting the observed changes in brain wave and neurotransmitter activity during MF protocol requires caution, as these changes may be attributed to impaired neural system function following cognitive tasks or may represent compensatory responses aimed at maintaining performance (Behrens et al., 2023). Therefore, these changes may not necessarily serve as direct indicators of MF development. Furthermore, identifying a single neurotransmitter responsible for all the neurochemical changes under MF conditions is complicated, given the interplay of multiple neurophysiological processes.

It is also important to acknowledge that the proposed theory does not fully explain the multifaceted nature of MF in sports. It is possible that MF develops from a combination of variables, and its underlying mechanism may vary among individuals and situations. To establish a comprehensive understanding of the mechanism underlying MF, future research should prioritise refining its measurement. The proposed theory regarding the potential mechanism of MF requires rigorous testing, specifically considering its multidimensional nature. More importantly, the theory regarding the accumulation of neurotransmitters such as adenosine in the brain, has not been validated in human studies due to ethical considerations. This theory has only been tested in animals, where systemic injection of adenosine was found to reduce the willingness to exert further effort in subsequent physical tasks (Font et al., 2008). Therefore, it remains unclear whether localised changes in dopamine and adenosine within specific brain regions occur in humans experiencing MF.

Another potential mechanism of MF is associated with perceived motivation, specifically the balance between effort and reward (Boksem et al., 2006; Boksem et al., 2008). According to this theory, MF occurs when the perceived level of effort required for a task outweighs the anticipated rewards, leading to a decline in perceived motivation and disengagement, resulting in MF (Boksem et al., 2006; Boksem et al., 2008). To elaborate, behaviour adjustments following MF protocols can interpreted as a response to an imbalance between energy expenditure and expected rewards. This framework suggests that MF involves a continuous evaluation of task-related costs and benefits, requiring the involvement of the prefrontal cortex and anterior cingulate cortex (ACC) to facilitate conscious decision-making (Boksem et al., 2008). This explanation aligns with the previously discussed framework, which attributes MF to increased workload in these brain regions (Martin et al., 2018).

However, previous research has reported inconsistent findings regarding the impact of additional motivators such as monetary incentives on mediating the effects of MF (Boksem et al., 2006; Brown et al., 2017). Previous research suggests that providing monetary incentives as a motivational reward can influence the behaviour of mentally fatigued individuals, leading to a significantly higher frequency of self-selecting a vigorous exercise intensity in a 22-minute cycling test following a 12-minute MF intervention (Harris et al., 2021). However, it is important to recognise that while mentally fatigued individuals adjusted their exercise intensity in response to monetary incentives, this did not necessarily lead to s significant increase in subsequent overall physical work (Harris et al., 2021).

Another investigation with 55 recreationally active individuals showed that acute decision-making regarding whether to exercise or not was unaffected by a 10-minute computerised cognitively demanding task when no additional motivation incentives were offered (Harris et al., 2019). This finding implies that motivation alone may not be the primary factor of an individual's decision to continue exerting effort, thereby challenging the theory that MF directly caused decreased motivation. Furthermore, mentally fatigued individuals often experienced a greater perception of effort during exercise (Harris et al., 2019; Brown et al., 2019) and presented reduced physical work output (Brown et al., 2019), in line with previous research (Van Cutsem et al., 2017). While motivational incentives can affect behavioural changes, they do not directly translate into enhanced physical performance. These findings raised questions about the universal effectiveness of monetary rewards as motivators, implying that not all individuals perceived financial incentives as sufficient to maintain effort. This highlights the highly individualised nature of motivation, which can vary significantly among athletes. Additionally, different athletes may be motivated by various factors, such as the desire to win or achieve personal best. The adaptability of behavioural strategies and the allocation of cognitive resources and physical effort under MF conditions remains unclear (Schiphoi-Godart et al., 2018), making it challenging to incorporate this theory to explain MF in sports.

Furthermore, the weak correlation between perceived motivational variables and the perceived fatigue index suggests that motivation alone is not a necessary contributor to the development of MF (Gergelyfi et al., 2015).

In summary, this section discussed two potential mechanisms of MF that have been proposed in the literature. The first mechanism reports that prolonged engagement in cognitively demanding tasks affects the dopamine and adenosine in the brain, subsequently affecting perceptions of exertion, MF, and other psychological responses. The second mechanism suggests that MF leads to a reduction in perceived motivation, prompting individuals to adjust their behaviour based on an evaluation of the effort-reward balance. While both potential mechanisms provide meaningful insights into the development of MF, further research is required to determine their relative contributions and interactions in real-world sports settings.

2.4 The Mental Fatigue Induction Methods

The following section will critically evaluate the selection and effectiveness of the MF protocols employed in the literature. This chapter will discuss the duration, specificity and limitations of these MF protocols, providing recommendations for their applicability in research and practical settings.

2.4.1 Effectiveness of Mental Fatigue Induction Methods

According to Table 2.1-2.4, previous research has implemented various cognitively demanding tasks as MF induction methods to examine the effects of MF on subsequent physical performance. These MF protocols have generally resulted in significant impairment in subjective ratings of MF, mood and fatigue-related variables. The laboratory-based MF protocols shared common features, requiring individuals to engage in a computerised cognitively demanding task for an extended duration, typically lasting at least 30 minutes. Besides, some MF protocols such as the Stroop-colour task, AX Continuous Performance task (AX-CPT) and N-back test, continuously challenge cognitive control by requiring participants to recall information from their working memory and respond to specific stimuli (Hotama et al., 2017). These tasks involve attention focus, decision-making and error detection (Hotama et al., 2017). Furthermore, previous research has often used emotionally neutral documentaries or videos as a control condition to evaluate the effectiveness of MF protocols, especially when a simplified version of the MF protocol was unavailable. While the majority of these MF protocols appear effective in inducing perceived MF, it remains important to critically evaluate their internal and external validity. Ensuring both validity is essential for determining whether these laboratory-based MF protocols accurately reflect the MF experienced in real-world sports settings.

2.4.1.1 Stroop task

The Stroop task has been well-established as an MF protocol, as it effectively challenges sustained attention, working memory and response inhibition by presenting individuals with a combination of four different colour words e.g. yellow, red, blue and green (Hotama et al., 2017; MacLeod & MacDonald, 2000). Due to the limited availability of MF protocol, the Stroop tasks have been widely used to induce MF, showing a significant increase in perceived MF in both untrained and trained populations following the MF interventions (Van Cutsem et al., 2017; Brown et al., 2020; Giboin et al., 2019). According to Table 2.1 to 2.4, three different versions of the Stroop task are frequently used in the literature as MF protocols: congruent (word and colour matched), incongruent (word and colour unmatched) and modified incongruent Stroop-colour task. The modified incongruent Stroop-colour task was similar to the incongruent Stroop task, but with one specific colour where participants were required to respond to the meaning of the word instead of the colour of the word (Martin et al., 2016). Both the incongruent and modified incongruent Stroop tasks are frequently employed in MF research because they present a greater cognitive challenge, requiring individuals to inhibit distractions caused by conflicting stimuli. However, due to the lack of direct comparative studies, it remains unclear which version is more cognitively demanding. Conversely, the congruent Stroop task is more straightforward, requiring less response inhibition, making it a commonly employed control condition in MF research (Table 2.1-2.4).

Comparing the perceived MF following an easier and a more challenging version of the Stroop task could help address inconsistencies in experimental settings observed in the literature. This approach may reduce challenges associated with selecting emotionally neutral documentaries or videos as control conditions. However, it is important to highlight that MF is a subjective psychological response, meaning that individuals may still perceive the congruent Stroop task as mentally demanding, despite it being considered less cognitively demanding than the incongruent version. Furthermore, the Stroop task may not be suitable for individuals with colour vision deficiency because its design relies on colour differentiation, which could affect response accuracy and task validity.

Moreover, the Stroop task is administered in two different ways: using a computer and keyboard to respond to stimuli or using a paper version where participants verbally respond to the stimuli. This thesis cannot conclude which is more effective in inducing MF because both computerised and paper versions have been shown to induce MF and provoke similar psychological impairments following the MF protocol (Smith et al., 2017; Campos et al., 2019; Smith et al., 2016; Slimani et al., 2018; Penna et al., 2018a; Penna et al., 2018b). However, the computerised Stroop task is encouraged because it automatically records response times and standardise sthe time interval between stimuli, reducing the risk of human-induced confounding variables such as variations in stimulus presentation of stimuli. These advantages enhance the internal validity and replicability of MF research.

The effectiveness of the Stroop task as an MF protocol has been widely used in previous research, with studies listed in Table 2.1-2.4 reporting a medium to very large increase (ES ranging from 0.73 to 2.764) in perceived MF ratings. These ratings were assessed using a 100-mm VAS (Van Cutsem et al., 2019; Filipas et al., 2018; Lam et al., 2021; Penna et al., 2018b; Lopes et al., 2020; Martin et al., 2019; Penna et al., 2018a; Veness et al., 2017; Badin et al., 2016; Campos et al., 2019; Coutinho et al., 2018; Kunrath et al., 2020a; Smith et al., 2017; Van Cutsem et al., 2019; Trecroci et al., 2020), the NASA mental demand subscale (Filipas et al., 2018; Martin et al., 2016; Pageaux et al., 2014; Pageaux et al., 2015; Staiano et al., 2018) or a 7-point scale (MacMahon et al., 2019; Schucker et al., 2016), showing significant increases in perceived following MF protocol across various studies. A more detailed discussion on the subjective measurement of MF is provided in section 2.5.2. Additionally, ten professional cricket players reported significantly higher perceived MF ratings with extremely large ES post-cognitive activity ($p < 0.001$)(Veness et al., 2017), implying that well-trained population can also be affected by the Stroop task. While the studies in Table 2.1-2.4 show that the Stroop task induces perceived MF in laboratory settings, it is important to acknowledge the low external validity associated with the Stroop task, which is a common limitation in laboratory-based MF investigations. This task requires participants to remain in a static position for extended durations, ranging from 4 to 90 minutes, as shown in Table 2.1-2.4. Also, the colour and word stimuli may not accurately replicate the cognitive demands athletes encounter during sports, where spatial awareness and multitasking are required.

2.4.1.2 AX Continuous Performance task and N-back task

The AX-CPT is a cognitive task that requires individuals to focus on the sequence of displayed letters and respond to the target stimuli. It has been utilised as an MF protocol in laboratory-based research and has frequently been shown to impair perceived MF, as summarised in Table 2.1-2.4 (Marcora et al., 2009; Martin et al., 2015; Smith et al., 2015). In the AX-CPT, the correct stimuli are the word 'X' presented following the word 'A', while any other order of presentation was considered as non-target stimuli (Marcora et al., 2009). Although the letter sequence was displayed in a pseudorandom order, there were discrepancies in the AX-CPT protocol utilised across studies. The display frequency of target stimuli and non-target stimuli was not standardised, with variations such as 20% (Martin et al., 2015, Brown et al., 2018; Macrora et al., 2009; Pageaux et al., 2013; Holgado et al., 2020; Le Mansec et al., 2018) or unspecified (Smith et al., 2015; MacMahon et al., 2014; Silva-Cavalcante et al., 2018). There were also inconsistencies in the display time for the words and the time intervals between each stimulus.

While MF induced by performing AX-CPT has demonstrated a moderate to very large impairment in perceived MF (Brown et al., 2018; Silva-Cavalcante et al., 2018; Le Mansec et al., 2018; Martin et al., 2015), the lack of standardisation in the protocol reduces the comparability between findings. In contrast to the Stroop task, no alternative version of the AX-CPT is available for a low or no cognitive demand task. Previous research had to utilise a time-matched control activity such as reading an emotionally neutral magazine or watching a emotionally neutral documentary or video as shown in Table 2.1-2.4. As discussed earlier, this reduced the effectiveness of the AX-CPT as an MF induction method as emotion is a subjective state that different individuals may interpret differently, potentially affecting the validity of the control condition.

Another important consideration is that there was no simplified version of AX-CPT, unlike the Stroop task where a simpler version was used as a control activity (section 2.4.1.1). The AX-CPT was performed continuously for a predefined period, ranging from 30-90 minutes, requiring participants to press buttons in response to stimuli. Conversely, watching a documentary or reading a magazine did not require constant physical output. The discrepancy in physical output and emotional state between the control condition and the AX-CPT may have contributed to the differences in experimental findings.

The N-back task shares a similar feature with the AX-CPT in that it challenges individual's working memory by requiring them to determine whether the letter presented on the screen matches the one they had seen previously (Holgado et al., 2019; Tanaka et al., 2012). However, according to Table 2.1-2.4, the N-back test was not frequently used to induce MF. This may be attributed to the lack of response inhibition in both simple and complex versions of the N-back task, which is considered a vital element in challenging the cognitive demand to induce MF. The unpopularity of the N-back task in previous research could also be attributed to the unstandardised experiment settings across studies. There were variations in display time and time intervals for letter presentation, such as 0.5 seconds with a 2.5-seconds interval (Holgado et al., 2019) or 1 second with a 3-second interval (Tanaka et al., 2012). The variation in test administration complicates the interpretation and comparison of results between studies. Moreover, there was conflicting evidence regarding the effectiveness of the N-back task. It might only be useful in measuring response time and accuracy rather than challenging individuals' working memory (Frost et al., 2021; Kane et al., 2007). Regarding its effectiveness as an MF induction method, Dallaway et al. (2022) found that the N-back test had a similar deleterious effect on perceived MF and subsequent 5-min handgrip endurance performance as the incongruent Stroop task following a 40-min intervention. However, this study measured endurance capacity via an isolated task rather than a whole-body endurance exercise, making it difficult to compare the effects between the two MF protocols. Nonetheless, the observed impairment in perceived MF with the 2-back task suggests it can be as effective as the Stroop task in inducing MF. As such, future research should not overlook it as a viable option as an MF induction method. In summary, future research should refine the test administration of the N-back test as it may provide a better control condition comparison compared to the AX-CPT.

2.4.1.3 Smartphone/ Video-based Intervention

In addition to the computerised MF induction method discussed above, there is growing evidence exploring the acute effects of exposure to smartphone and video-based tactical tasks on perceived MF and subsequent sports performance. These investigations have adapted similar experimental setting to most MF research, using an emotionally neutral documentary or video as a control activity for comparison. Similar to the findings observed following computerised cognitively demanding tasks, the subjective ratings of MF and sports performance, including response time and accuracy, were significantly impaired following smartphone use (Gantois et al., 2021; Fortes et al., 2020; Fortes et al., 2021; Fortes et al., 2021) or video-based tactical tasks (Faro et al., 2020; Ciocca et al., 2022; Fortes et al., 2021). These studies reported a moderate to very large increase in perceived MF following the interventions, implying that these MF protocols could negatively affect participants' MF levels. However, it is noteworthy that the timing between control and experimental trials varied inconsistently across studies. For instance, some studies implemented a one-week wash-out period between control and experimental trials (Gantois et al., 2021; Fortes et al., 2020; Faro et al., 2022), while another study allowed only a 24-hour interval (Ciocca et al., 2022). Although the researchers did not inform participants about the specific condition during the trials, the noticeable changes in activity, such as switching from watching a documentary on TV to continuous smartphone use or responding to a video-based tactical task, could potentially influence participants' ratings of MF. There is a possibility that participants might have been aware that a particular condition was the MF trial, where perceived MF was expected to be high. Further details regarding the issues related to the control condition will be discussed in section 2.4.1.5. Consequently, these variations may serve as confounding variables and could impact the accuracy of the study findings.

In line with the findings discussed in section 2.2.3, the MF induced through smartphone usage did not negatively affect anaerobic performance, i.e. CMJ and sprinting (Fortes et al., 2020; Fortes et al., 2021). Importantly, the use of a smartphone as an MF intervention requires participants to engage with social media such as Twitter, Instagram and Facebook for an extended period (Gantois et al., 2021; Fortes et al., 2020; Fortes et al., 2021; Fortes et al., 2021). Although this MF protocol was performed under the supervision of researchers, it cannot be considered emotionally neutral because the content of the task was not assessed before the experiments. A similar limitation was observed in Faro et al. (2020), who utilised a video-based tactical game as an MF intervention. It cannot be neglected that the video game could provoke psychological responses in participants due to winning or losing. Previous research has indicated watching emotionally suppressed videos could negatively influence subsequent endurance performance (Schlichta et al., 2022), suggesting that fluctuation in emotions could impair both physical and psychological responses. Therefore, it remains possible that the content of social media during smartphone usage and video-based intervention could influence individuals' psychological responses during the tasks. Conversely, ten national level under-18 soccer players showed a very large increase (ES = 2.09) in perceived mental effort but did not significantly impair subsequent SSG performance following a video-based tactical task (Ciocca et al., 2022). It is essential to note this study measured mental effort instead of MF, so it cannot determine whether the absence of impairment is related to MF. To reduce the potential confounding variables, future research should evaluate the emotional neutrality of the content in MF protocols to improve the validity and reliability of the findings.

Importantly, these studies using smartphone and video-based tasks as MF protocols did not mention whether the protocol was performed under a silent condition. There is a possibility that music was involved while using social media, as platforms such as Facebook and Instagram frequently include music or audio tracks in their content. Since these studies did not specify whether the audio was disabled during the experiment, this could be a potential confounding factor. Previous research has shown that the involvement of music can mediate the negative effects of MF (Lam et al., 2021). Therefore, the involvement of audio tracks or music during the MF protocol could potentially influence the results. Regarding the video game intervention employed by Faro et al. (2020) and Fortes et al. (2021), it is important to acknowledge the weaknesses associated with these interventions. Video games provide constant visual stimulation and may induce various psychological responses, which could affect the accuracy of evaluating the effectiveness of the MF protocol. In summary, the evidence regarding the effectiveness of smartphone and video-based intervention as MF protocols remains inconclusive due to the potential confounding variables mentioned, including emotional fluctuations and the involvement of sounds and music. Without a careful assessment of the content of the smartphone activity and video task before the experiments, accurately evaluating the effectiveness of these MF protocols becomes challenging.

2.4.1.4 Individual-specific task

The majority of the investigations have focused on using computerised mentally demanding tasks to induce MF (Van Cutsem et al., 2017; Habay et al., 2023; Giboin et al., 2019). However, two studies have specifically designed individual-specific MF protocols aligned with the characteristics of the participants, such as involving sport-specific decision-making (Ciocca et al., 2022) or activities routinely performed in sports (Couthin et al., 2017). These studies reported significant impairments in perceived MF (ES = 3.2) and mental effort (ES = 2.09) following the individual-specific protocol (Coutinho et al., 2017; Ciocca et al., 2022). Ciocca et al. (2022) found that completing a 30-minute video-based soccer tactical task significantly increased mental effort. However, no negative effects were reported on subsequent SSG and soccer-specific performance. It is essential to interpret this finding with caution, as the investigation used the terminology "mental effort" instead of "mental fatigue". This difference indicates that participants experienced an increase in mental effort but not necessarily MF following the MF induction method, which may explain the absence of impairment in subsequent sports performance.

In contrast, Coutinho et al. (2017) utilised light aerobic exercise as a control condition to evaluate whether an individual-specific approach involving both physical and cognitive load along with ball control to navigate obstacles could significantly induce MF among trained youth soccer players (Coutinho et al., 2017). This provided insight that the MF protocol may not limited to the task intentionally designed to increase cognitive demand. Performing an individual-specific task for an extended period could also induce MF. This shows the potential of incorporating sport-specific activities to induce MF and reduce the reliance on computerised cognitively demanding tasks. However, it is vital to acknowledge that determining the appropriate volume and intensity for an individual-specific MF protocol can be technically difficult due to the uncertainty of the development and understanding of MF. To increase the validity of the findings, future research could consider the tasks that athletes regularly perform in their daily routines such as warm-up protocols to investigate MF. Otherwise, intentionally developing a protocol to investigate MF may suffer from similar low specificity as computerised MF protocols. Further research is warranted to explore the effectiveness of incorporating individual-specific activities for examining MF in sports.

2.4.1.5 Considerations of Control Conditions Across Studies

As discussed in sections 2.4.1.1 to 2.4.1.4, the literature revealed the utilization of at least four different types of MF protocols, as outlined in Table 2.1-2.4. It is crucial to highlight that the activity chosen for the control condition can significantly impact the accuracy of interpreting the study findings. According to Table 2.1-2.4, previous research commonly employed activities such as reading or watching an emotionally neutral documentary or magazine. However, it is essential to note that emotion is a subjective experience, and what is perceived as emotionally neutral by researchers may not be perceived similarly by participants. Importantly, it is difficult to precisely define the neutral emotional state of the participants.

It is observed that frequently used MF interventions, such as AX-CPT, have limitations, particularly in the absence of an easier version that requires less cognitive effort, unlike the Stroop task discussed in section 2.4.1.1. In the case of the Stroop task, a congruent version can be used as a comparison to the incongruent version. Consequently, researchers have had to explore alternative control activities, such as watching a documentary for the same duration, for comparison with AX-CPT. Although the control activity in studies that utilised the Stroop task or AX-CPT were performed on the same device, i.e. a laptop, in both the control and MF conditions, the feasibility of these control activities remains unclear, as they may impact participants' psychological responses, including their perception of MF. Moreover, previous research has attempted to implement a more realistic approach, such as using a smartphone or responding to a video-based tactical task to induce MF in a laboratory setting as shown in section 2.4.1.3. However, there is inconsistency in the use of modalities for control and experimental trials, such as employing a smartphone for experimental trials and a varying-sized TV screen for documentary watching in the control condition (Gantois et al., 2021; Fortes et al., 2020; Fortes et al., 2021). Considering MF is a subjective feeling, the change in equipment during the experiments may influence participants' expectations, potentially affecting their ratings, as they may anticipate greater MF in a more demanding task compared to a less demanding one.

2.4.2 The Duration of Mental Fatigue Induction Methods

According to Tables 2.1-2.4, the length of the MF protocols used in the literature varies greatly, ranging from 4 to 90 minutes. Previous systematic review that analysed the MF protocol lasted at least 30 minutes and revealed significant impairment in subsequent physical performance (Van Cutsem et al., 2017). However, there is no consensus in the literature on the most effective duration for inducing MF in laboratory settings. Although a longer MF protocol may eventually elicit MF, it is unclear if the observed MF is largely due to increasing cognitive load or a subjective experience of boredom and/or demotivation (Borragán et al., 2017). Additionally, other research has shown even shorter MF protocols (< 30 minutes) might cause variable degrees of impairment in perceived fatigue and athletic performance (Boat et al., 2020; Boat & Taylor, 2017a; Graham et al., 2017; Shin et al., 2019; Zering et al., 2017). Although most reviews suggest higher ratings of MF negatively impact sports performance (Brown et al., 2020; Giboin & Wolff, 2019; Habay et al., 2021; Van Cutsem et al., 2017), it is unclear if longer MF protocols (> 30 min) would have a greater detrimental effect on perceived MF and subsequent sports performance because this effect was not seen in some studies with longer MF protocols (Filipas et al., 2018; Head et al., 2017; Holgado et al., 2020; Kosack et al., 2020; Martin et al., 2019; Silva-Cavalcante et al., 2018). Based on a meta-analysis (Giboin et al., 2019), it is possible that the development of MF is not only linked to the length of the MF protocol but also related to the cognitive effort exerted by the participant throughout the task. On the other hand, it appeared that previous research did not consistently report the extent of changes in MF following the MF protocol, which makes comparing the magnitude of changes across studies challenging. As such, the question of whether longer MF protocols may produce greater perceived MF than shorter ones remains questionable.

Previous studies showed a significant increase in perceived MF following shorter MF protocols (Boat et al., 2020; Boat & Taylor, 2017a; Graham et al., 2017; Shin et al., 2019; Zering et al., 2017), supporting the finding of previous meta-analysis that found no correlation between the length of the MF procedure and the development of MF (Giboin & Wolff, 2019). However, it is essential to highlight an important weakness in this analysis, which included a wide range of participants, from untrained to competitive individuals (Giboin & Wolff, 2019). The variety in the individuals' training histories may limit the reliability and generalisability of the conclusion. While it has been concluded that using the length of the MF protocol alone to determine the development of MF may be less accurate, no study has provided data disproving the claim that a short MF protocol might elicit MF as effectively as a longer duration. The findings presented in Tables 2.1-2.4 indicate that perceived MF is likely to be affected as long as the MF protocol sufficiently challenges an individual's cognitive resources, irrespective of its duration. Instead of focusing on the duration of the MF protocol, future studies should prioritise exploring the factors that naturally challenge individuals' cognition.

2.4.2.1 Protocol Specificity

According to Tables 2.1 to 2.4, MF has often been induced using laboratory-based cognitively demanding tasks such as the AX-CPT and the congruent and incongruent Stroop-color task. Both prefrontal brain wave activity and subjective ratings of MF have increased during these protocols (Hotama et al., 2017; Taya et al., 2018), supporting the neural mechanism of MF proposed by Martin et al. (2018) and Smith et al. (2018), which suggests MF is closely related to the prefrontal cortex including the ACC. However, a significant limitation of these MF protocols is their lack of relevance to real-world conditions. The protocols mainly involve repetitive and monotonous actions carried out in a controlled laboratory setting. The repetitive nature of the MF protocol raises concerns about whether the variations in perceived MF ratings were caused by MF or boredom. This is because computerised MF procedures may not adequately replicate the complexity of MF encountered in daily life or the cognitive demands experienced in sports.

Additionally, previous research with 82 recreationally active individuals found that offering monetary incentives could not mediate the extent of the increase in perceived MF after a 10-minute Stroop task (Brown et al., 2017). A similar investigation with 77 recreationally active individuals found no improvement in physical performance when monetary incentives were provided, but it did demonstrate a greater intention to select a more intense cycling exercise intensity following a 12-minute MF protocol (Harris et al., 2021). There remains a likelihood that increasing participant involvement in MF procedures could yield different results, suggesting these protocols' specificity may be poor since other confounding variables can easily influence the results. The majority of the MF protocols discussed above, including the AX-CPT and Stroop-color task, primarily relied on testing participants' ability to maintain attention for lengthy periods in order to induce MF (Hotama et al., 2017). Participants may not consider these tasks relevant to their regular routines or engage in the protocols with the same level of focus as they would in everyday life or sports. This could lead to a mismatch between the actual MF experienced in athletics and the MF induced in the laboratory. Consequently, the findings from laboratory-based research may not apply to sports where MF develops differently. Explaining MF in sports based on controlled laboratory experiments may oversimplify the concept of MF in sports and neglect the various cognitive demands encountered in sports.

Furthermore, the vagueness of the MF procedure regarding the individuals' backgrounds and training histories is an additional cause of concern. Previous studies sought to overcome the limitations of laboratory-based MF protocols by integrating activities relevant to sports or daily life to improve the specificity of the MF protocol. Previous research has used whole-body coordination tasks (Coutinho et al., 2017), smartphones (Fortes et al., 2021; Fortes et al., 2020; Gantois et al., 2021; Trecroci et al., 2020) and video-based tactical tasks (Faro et al., 2022; Ciocca et al., 2022) as MF protocols. Unlike the previously discussed cognitively demanding activities, these approaches did not directly challenge individuals' concentration and attention. Alternatively, they required participants to engage in daily activities or sports that they would normally perform for an extended period, ranging from 20 to 60 minutes. These protocols have greater external validity than computerised MF protocols including activities like using social media on smartphones (Fortes et al., 2020; Fortes et al., 2021), sport-specific tactical planning tasks (Faro et al., 2022; Cicocca et al., 2022) and sport-specific physical activity (Coutinho et al., 2017).

Interestingly, regardless of the participants' training background, similar impairment in subjective ratings of MF and subsequent physical performance were observed (Fortes et al., 2021; Gantois et al., 2019; Trecroci et al., 2020; Faro et al., 2020). However, studies utilising video-based tactical tasks as the MF methodology yielded inconsistent results. For example, Ciocca et al. (2022) discovered greater mental effort but improved successful passes and total number of passes during subsequent SSG after a 30-minute video-based tactical exercise with 10 national-level football players. It remains unclear whether the improved football performance following the soccer-specific tactical task indicated that MF does not always cause impairment in football performance because this study did not specifically examine perceived MF. This contrasts with the results from Faro et al. (2020) with 14 national league basketball players, where response time and accuracy were impaired following a 60-minute video game task.

It is important to acknowledge the MF protocol used by Ciocca et al. (2022) involved a soccer-specific tactical task in which participants had to respond to in-game situations by selecting the best tactical solution for game continuation. Conversely, Faro et al. (2020) only required participants to play a basketball video game on PlayStation. Although these MF protocols matched the individual’s background, the selection of performance assessments may have contributed to the inconsistent findings. For example, Ciocca et al. (2022) used soccer SSG to examine soccer performance, whereas Faro et al. (2020) used a standardised visuomotor task to assess basketball performance. Compared to a visuomotor activity, the presence of an opponent in football SSG offers greater variability and unpredictability. While it cannot be fully ruled out that employing a video-based tactical game as an MF protocol might promote similar sport-specific tactical thinking (Faro et al., 2020), it is essential to consider winning or losing in the video game could cause psychological responses. To summarise, more study is needed to understand how the specificity of MF protocols affects subsequent performance.

2.4.3 Limitations

It has been discovered that the duration of the MF protocols lacks standardisation, with previous research using varying durations to induce MF. Previous studies have found that the development of MF does not necessarily relate to the complexity of cognitive effort, but rather that continual engagement of cognitive effort could cause MF (Borragán et al., 2017). This shows that the duration of the MF protocol is essential in determining the level of MF experienced. However, this explanation is debatable, as discussed in section 2.4.2. As stated in section 2.2, a short-duration MF protocol can lead to an increase in perceived MF with comparable impairments in subsequent physical performance, supporting previous findings that MF is related to the amount of effort exerted rather than the time spent (Giboin et al., 2019). This implies that the type of activities performed during the MF protocol may be more important.

Furthermore, a common problem found in the majority of the research reviewed is that the MF protocol lacks specificity, limiting the generalizability of findings to real-world scenarios. This is because MF was caused by engaging in a repeated computerised cognitively demanding task. Although there was a negative impact on perceived MF ratings and physical performance following the MF protocols, the results from these irrelevant activities made it more difficult to explain the MF experienced in sports. Furthermore, the lack of subjective measures of boredom in most investigations raised concerns about whether the increased ratings of MF and reduced physical performance were simply a consequence of boredom rather than MF. The subjective measurement is specifically discussed in section 2.5.2. Moreover, the MF protocol was administered in a controlled environment with few external factors, such as distraction, which may not completely reflect the real-world consequences and impairments associated with MF.

Another significant limitation observed in the research discussed in Tables 2.1-2.4 is the lack of reporting of participants' prior knowledge of MF. It is important to highlight the literature presents a variety of theoretical frameworks for MF (Boksem & Tops, 2008; Martin et al., 2018; Smith et al., 2018). The absence of information or explanation about the theoretical foundation of MF within research may create confounding variables, as differing conceptualizations and interpretations of MF can directly the validity and reliability of the results. Consequently, the observed differences in MF ratings may be related to the participants' initial perceptions of MF rather than the real effects of the MF intervention. Due to the absence of this information, there is a possibility that participants could mistake other psychological responses, such as boredom, for MF. Furthermore, the variability in the definition of MF and participants' knowledge of MF compromises the comparability of results across research. In summary, these confounding variables may affect the effectiveness of the MF intervention and obscure its influence on both physical and psychological responses.

2.4.4 Recommendations

While it is plausible that a prolonged computerised mental exertion task can influence subjective ratings of fatigue and endurance-based performance, it remains unclear whether MF in sports is a distinct phenomenon from other types of MF. A previous meta-analysis found no correlation between the duration of the MF protocol and the development of MF (Giboin & Wolff, 2019), casting doubt on the hypothesis that the extent of MF is related to the time spent on cognitively demanding tasks. Regarding the specificity of the MF protocol, previous studies have employed more realistic approach to explore the effects of MF, such as exposure to social media via smartphone (Fortes et al., 2021; Fortes et al., 2020; Gantois et al., 2021; Trecroci et al., 2020), individual-specific video tactical games (Faro et al., 2020; Ciocca et al., 2022) or sport-specific warm-up protocols (Coutinho et al., 2017). As a result, additional studies are necessary to determine if daily work generates similar MF to computerised MF protocols. This suggests that research should not be limited exclusively to computerised MF induction methods (Brown et al., 2020; Habay et al., 2021; Van Cutsem et al., 2017), given that individuals rarely engage in irrelevant computerised cognitively demanding tasks for extended periods before training or competitions. It is important that the primary focus of research shifts to investigating the occurrence of MF in sports, rather than attempting to generate MF in the laboratory using different computerised MF protocols.

It has been demonstrated that the research utilising computerised MF induction protocol can acutely induce perceived MF based on the evidence discussed in sections 2.4.1 and 2.4.2. However, it is important to note that MF can also develop naturally when engaging in everyday activities such as using a smartphone (Fortes et al., 2020; Fortes et al., 2021). Furthermore, everyday activities like schooling are perceived to be a potential cause of MF, according to a previous study conducted with academy football players (Thompson et al., 2020). This indicates that MF may occur naturally in both daily life and sports without the need for intentional induction. Furthermore, Fortes et al. (2021) revealed that repetitive use of social media for 30 minutes during 20 training sessions over four weeks led to increased session RPE and impaired decision-making in attack and passing performance in volleyball. These findings highlight the potential impact of daily activities such as smartphone use on athletes' cognitive and physical performance.

Furthermore, there is increasing evidence showing that participating in sports can induce MF (Thompson et al., 2020; Russell et al., 2022; Garcia et al., 2023; Abbott et al., 2018; Abbott et al., 2020). This implied that the focus on improving the ecological validity of the laboratory-based MF protocol may be of lesser importance if the aim is to evaluate the effects of MF on sports performance. It also reflects that sports can serve as a model to better investigate the occurrence of MF in sports, both acutely and chronically. Future studies with athletes may provide meaningful insights into whether MF develops in the athletic environment. This approach not only addresses individual variability but also reflects the complex and unpredictable nature of cognitive and physical demands that athletes encounter in sports.

The longitudinal investigation approach overcomes the uncertainty of determining a specific time to induce MF and instead focuses on the impact of training and competition on MF. Although Smith et al. (2019) discovered that the artificial MF induction method could have an after-effect on psychological responses for up to 45 minutes after the task, the practical relevance of these findings is limited due to their lack of representation of real-world sporting activities. As discussed in sections 2.4.1 and 2.4.2, most evidence has focused on MF as a one-time event, neglecting the potential accumulative effects of continuous cognitive demands across multiple days of training or competition. While these approaches help improve knowledge of the acute effects of MF, they may not adequately replicate the MF encountered by athletes in real-world sports contexts. Investigating the occurrence of MF during training or competition not only increases the validity and relevance of the findings but also expands opportunities for investigating the effect of MF on recovery.

2.5 Measurement of Mental Fatigue

2.5.1 Objective Measurement

Table 2.5 summarised the research that has employed objective measures of MF. Previous research has focused on other objective measurements of MF due to ethical and logistical difficulties with directly measuring brain activity in individuals. These measurements include changes in reaction time, response accuracy, blood glucose levels, HR, and brain wave activity. The following sections will discuss the objective measures of MF, exploring how each measure contributes to our understanding of MF.

Table 2.5 Overview of the objective mental fatigue measurement (review articles are excluded, n = 40)

Study & Study design	Participant (Characteristics, number, age, training history)	Control condition	Induction method	Objective measurement	Outcome (CON vs INT)
Alder et al. (2021) Randomised counterbalanced design	**Soccer players** 16M, Age: 22.4 ± 2.5, 14 ± 3.6 years of experience in soccer, Average training hours: 3750 ± 423, Average played competitive matches: 340 ± 13.2	20 min anticipation test film (verbally anticipate the action of the ball carrier of a 11 vs 11 soccer match)	30 min incongruent Stroop task	Response accuracy, mean HR, visual search behaviours during approximately 10 min verbal anticipation soccer clips	↓ Response accuracy ($p = 0.02$, $d = 0.55$) CON: 78.2 ± 9.1%; INT: 60.6 ± 7.7% ~ Mean HR ($p = 0.09$, $d = 0.01$) CON: 30.12 ± 5.51% HRmax; INT: 30 ± 5.62% HRmax Visual search behaviours: ↑ Number of fixations ($p = 0.02$, $d = 0.29$) CON: 4.95 ± 1.24; INT: 7.41 ± 3.03 ~ Duration of fixations ($p = 0.17$, $d = 0.13$
Batista et al. (2021) Randomised crossover design	**Orienteers** 15M, Age: 30 ± 8, > 3 years of competition experience	10 min observational task and 20 min relaxation	30 min incongruent Stroop task	Mean and maximum HR	↑ Mean HR (ES = 0.49) CON: 67.1 ± 9.2 bpm; INT: 72.2 ± 11.6 bpm ↓ Maximum HR (ES = 0.28) CON: 99.9 ± 14.9 bpm; INT: 96.3 ± 10.8 bpm
Boat et al. (2021a) Randomised counterbalanced crossover design	**Hockey players** 13M, Age: 20 ± 1, competing in national or regional leagues	4 min Congruent Stroop task	4 min IST	Response time and accuracy during Stroop task	↑ Response time ($p < 0.001$) CON: 1584 ± 261 ms; INT: 1958 ± 310 ms ↓ Accuracy ($p = 0.016$) CON: 97.8 ± 2.1%; INT: 96.2 ± 3.8%
Brown and Bray (2019) Randomised crossover design	**University students** 13M12F, Age: 20.16 ± 1.48, involved in physical activity: 92.13 ± 44.24 min per week	Watching a 50-minute documentary	50 min AX-CPT	Average HR Response accuracy during AX-CPT	~ Average HR ($p = 0.45$) ↓ The number of correct responses ($p = 0.05$, $d = 0.44$) First 10min: 96.88 ± 2.42 Final 10min: 94.44 ± 5.74
Campos et al. (2019) Randomised counterbalanced design	**Judo Players** 9M4W, Age: 19.5 ± 3.0, 7.2 ± 3.9 years of experience	Watching a 30-minute documentary	30 min MIST (paper version)	Blood Lactate Blood Glucose Salivary Cortisol	Increased [BLa] ($p < 0.001$) ~ Blood Glucose ($p = 0.433$) ~ Salivary Cortisol ($p = 0.305$)
Clark et al. (2019) Randomised crossover design	**Untrained** 10M, Age: 25.8 ± 4.6, Trained < 3 hours/week **Trained** 10M, Age: 27.4 ± 6.3, Trained > 9.5 hour/week	Watching a 30-minute documentary	30-minute N-back task and a mixture of congruent and incongruent	Mean HR Plasma lactate Glucose K+ Na+ Cortisol Cerebral-oxygenation	↑ Mean HR ($p < 0.005$) -UNT ~ Plasma lactate concentration ~ Plasma glucose concentration ~ Plasma sodium concentration ~ Plasma cortisol concentration

			Stroop colour task (alternated on a 2- and 3-min loop)		~ Cerebral oxygenation (change in concentration of tissue oxyhemoglobin, tissue total hemoglobin, tissue deoxyhemoglobin) UNT: ↑ Plasma potassium concentration ($p = 0.002$)
Coutinho et al. (2017) Randomised counterbalanced crossover design	**Youth Soccer Players** 12M, Age: 15.9 ± 0.8, 8.9 ± 2.4 years of experience in soccer	20 min light aerobic exercise	20 min whole-body coordination task	CMJ	~ CMJ jump height ($p > 0.05$)
Fairclough and Houston (2004) Randomised counterbalanced design	**Healthy Individuals** 9M21F, Age: 24.5 years	45 min CST	45 min IST	Response time and accuracy during Stroop task	Slower RT ($p < 0.01$) CST: 619.2 ± 12.5ms; IST:662 ± 12.4ms ~ Response accuracy ($p > 0.05$) CST: 8.7 ± 0.82; IST: 15.4 ± 2.5
Faro et al. (2020) Randomised counterbalanced design	**National Basketball Players** 14M, Age: 24.3 +4.1, 6.5 + 1.9 years competitive experience in second division of National League of Brazil	Watching 60 min documentary	60 min basketball-based video game on PlayStation 4	Stroop EEG	EEG: ↑ Theta wave ($p = 0.001$, $\eta^2p = 0.21$) Stroop: ~ Response accuracy ($p = 0.53$, $\eta^2p = 0.003$) ↑ RT ($p = 0.001$, $\eta^2p = 0.11$)
Filipas et al. (2018) Randomisesd counterbalanced crossover design	**Youth Rowers** 11M6F, Age: 11 ± 1.06, > 2 training session per week in local club	60-minute drawing task with grey pencil	60 min MIST	Response time and accuracy during CST	Within 60 min MIST: ~ RT over time ($p = 0.094$, $\eta^2p = 0.131$) ↑ Accuracy over time ($p = 0.001$, $\eta^2p = 0.298$)
Filipas et al. (2020) Randomised counterbalanced design	**Soccer Players** 12 from U14; 12 from U16; 12 from U18; > 3 years of experience in competing at national level	15-minute reading an emotionally neutral online magazine	30 min MIST	Accuracy and reaction time during the task	~ Accuracy between different age group ($p > 0.05$) ~ Reaction time between different age group ($p > 0.05$)
Fortes et al. (2020) Randomised crossover design	**Professional Swimmers** 14M11F, Age: 20.4 ± 2.06, 8.4 years of experience in international and national level swimming competition	Watching a 30 min coaching videos	30 min usage of social media application (WhatsApp, Facebook and	30 words with 200ms interval of CST and IST before and after each condition: Response time, accuracy	Slower response time ($p = 0.01$, $\eta^2 = 0.42$) ~ Accuracy ($p = 0.32$, $\eta^2 = 0.04$)

			Instagram) on smartphone		
Fortes et al. (2021) Randomised crossover design	**Regional to national level boxers** 13M8F, Age: 23.33 ± 3.46, 8.9 years of experience in national and regional tournaments	Watching a 30 min coaching videos	30 min usage of social media application (WhatsApp, Facebook and Instagram) OR 30 min playing video games	CMJ 30 words with 200ms interval of CST and IST before and after each condition: Response time, accuracy	~ CMJ performance ($p = 0.96$) but a decrease in CMJ is observed in all post MF induction conditions compared to pre ($p = 0.001$) ~ Accuracy ($p = 0.58$, $\eta^2 = 0.02$) CON: 90. 95 ± 5.61% (PRE); 92.38 ± 4.96% (POST) Smartphone: 92.38 ± 4.96% (PRE); 92.45 ± 5.8% (POST) Videogame: 93.10 ± 5.41% (PRE); 92.53 ± 4.19% (POST) Slower response time in smart phone and video games compared to CON ($p = 0.001$)
Fortes et al. (2021) Randomised counterbalanced design	**Junior National Volleyball Players** **24M, Age: 15.7** ± 0.6, average training frequency: 4.9 ± 0.2 sessions/week, trained 10.3 ± 0.8 hours/week, 3.4 years in national to regional competitive experience	Watching a 30 min videos	30 min usage of social media application (WhatsApp, Facebook and Instagram)	CMJ 130 words with 500ms interval Stroop task before and after each condition: response accuracy and response time	~ CMJ ($p = 0.91$) ~ Response accuracy ($p = 0.37$, ES = 0.07) ↑ RT ($p = 0.04$, ES = 0.32)
Gantois et al. (2019) Randomised counterbalanced design	**Professional Soccer Players** 20M, Age: 22.6 ± 3.3, ≥ 3 years of professional soccer training experiences	Watching a 30-minute advertising video	15- or 30-minute IST	Inhibitory control performance during 15- and 30-min Stroop: Response time, accuracy	Slower response time in 30 min IST than 15 min IST ($p = 0.03$) ~ accuracy ($p > 0.05$)
Graham et al. (2017) Single-blind randomised design	**University students** 21M29F, Age: 20.98 ± 2.83	5-minute congruent Stroop task	5 min MIST	Stroop task performance	↓ Completed trials ($p < 0.001$, $d = 2.59$) ↑ Errors ($p < 0.001$, $d = 1.92$)
Hachard et al. (2020) Randomised crossover design	**Health individuals** 13M7W, Age: 21.8 ± 1.7	Watching a 90-minute documentary	90 min AX-CPT	Percentage of correct responses and time of correct response during AX-CPT	↓ Percentage of correct responses ($p = 0.04$) ↑ Time of correct response ($p = 0.03$)
Holgado et al. (2019) Randomised counterbalanced design	**Cyclists** 28M, Age: 27.0 ± 7.4, trained > 6 hour per week	20 min 1-back test	20 min 2-back test	Response accuracy during N-back test	↓ Percentage of correct responses ($BF_{01} = 4490$) CON: 96%; INT: 88%

Holgado et al. (2020) Randomised counterbalanced design	**Reactional Active** 24M6F, Age: 23.5 ± 6.3, Trained > 6 hour per week	Watching a 90-minute documentary	90 min AX-CPT	Response accuracy	~ Response accuracy in the first 15 min and last 15 min (BF_{01} = 4.04)
Kosack et al. (2020) Randomised crossover design	**Elite Badminton Players** 19M, Age: 20 ± 2.8; 12.5 ± 3.5 years of experience with top 100 national Danish ranking	Watching a 60-minute documentary	60 min MIST	Response time and accuracy during MIST	Within MF condition: ~ Response accuracy over time ($p = 0.07$) Faster response time over time ($p = 0.002$)
Kunrath et al. (2020a) Non-randomised controlled design	**Soccer Players** 18M, Age: 21.8 ± 2.5, participated in national and state league tournaments	Watching a 30 min documentary	30 min MIST	Response accuracy during Stroop task, Visual field (ability to react to stimuli at the edge of the visual field) Vienna Test system – The Peripheral Perception test version S1 before and after MIST	~ interaction between time and correct accuracy in IST ($p = 0.761$, $d = 0.031$) Vienna Test system – The Peripheral Perception test version S1 before and after MIST: ↓ Visual field ($p = 0.035$) Sum of right and left visual angles Tracking deviation time (chase the object) ($p = 0.884$) Reaction time ($p = 0.705$) Omitted reaction (off reaction) ($p = 0.814$)
Lopes et al. (2020) Randomised controlled crossover design	**Mid- and Long-Distance Runners** 16 Men, Age: 25 ± 1, weekly training distance: 96 ± 9 km 15 Women, Age: 25 ± 1, Weekly training distance: 88 ± 7 km	Watching a 45-minute documentary	45 min mixture of congruent and incongruent Stroop task	Reaction time and accuracy during Stroop task	~ Reaction time ($p = 0.526$) ↓ Accuracy ($p = 0.027$)
MacMahon et al. (2019) Randomised counterbalanced design	**Active individuals** 10M3F, Age: 19.92 ± 1.75, 10.8 ± 4.48 years of playing experience	30-minute congruent Stroop task	30 min IST	Reaction time and response accuracy during cognitive task	↑ Mean reaction time ($p < 0.05$) CON: 817.28 ± 107.66 ms; INT: 1225.69 ± 244.21 ms ↓ Percentage of correct response ($p < 0.05$) CON: 98.56 ± 0.12%; INT: 87.6 ± 0.05% IST shows larger latency ($p < 0.001$, partial $\eta^2 = 0.72$) and incorrect responses ($p < 0.001$, partial $\eta^2 = 0.91$) than CST
MacMahon et al. (2014) RCT	**Recreational Active**	6-minute AXCPT & 84-	90 min AX-CPT	Reaction time and accuracy during AXCPT	Within MF condition: ~ Reaction time ($p = 0.73$)

	18M2F, Age: 25.4 ± 3.24, Trained 2.84 ± 1.79 hour/week	minute documentary			~ Response accuracy in the first and final 3 min of condition ($p > 0.05$) CON: 93 ± 6% (first 3 min); 96 ± 6% (last 3 min) INT: 90 ± 11% (first 3 min); 95 ± 7% (last 3 min)
Martin et al. (2015) Randomised crossover design	**Triathletes** 7M5F, Age: 23 ± 3, participate high-intensity training ≥ 3 time a week	Watching a 90-minute documentary	90 min AX-CPT	Reaction time and accuracy during AX-CPT	Within MF condition: reaction time ($p = 0.095$) ~ Accuracy in the first to the last 15 min of the cognitive task ($p = 0.152$, $d = 0.445$)
Martin et al. (2016) Randomised crossover design	**Professional Road Cyclists** 11M**,** Age: 23.4 ± 6.4, > 5 years of cycling experience **Recreational Road Cyclists** 9M, Age: 25.6 ± 5.3, ~2 years of cycling experience	Sit quietly and focus on a black cross for 10-minute	30 min MIST	Reaction time and accuracy during MIST	Professional: Faster reaction time ($p < 0.001$) ~ Accuracy Recreational: ↑ Reaction time ($p = 0.019$) ~ Accuracy Professional completed more correct responses than recreational ($p = 0.001$) and a significant group difference in RT ($p = 0.023$, $\eta^2p = 0.165$)
Marcora et al. (2009) Randomised crossover design	**Recreational Active** 10M6F, Age: 26 ± 3	Watching a 90-minute of emotionally neutral documentary	90 min AX-CPT	accuracy during AX-CPT blood glucose Average HR	↓ blood glucose ($p < 0.001$) ↓ Response accuracy ($p < 0.001$) First 15 min: 94.8 ± 3.4% Last 15 min: 88.9 ± 4.5% ↑ average HR ($p = 0.046$) CON: 62 ± 8 INT: 65 ± 8
Pageaux et al. (2014) Randomised crossover design	**Recreational Active** 8M4F, Age: 21 ± 1, Trained ≥ 2 per week for last 6 months	30-minute congruent Stroop task.	30 min IST	HR Blood glucose concentration Reaction time and response accuracy during cognitive task	↑ HR ($p = 0.003$) ~ Blood glucose concentration ($p = 0.812$) ↑ Reaction time ($p < 0.001$, $\eta^2p = 0.862$) ~ Response accuracy between condition ($p = 0.138$, $\eta^2_p = 0.189$) or over time ($p = 0.562$, $\eta^2_p = 0.050$)
Pageaux et al. (2015) Randomised counterbalanced design	**Recreational Active** 12M, Age: 25 ± 4, Trained ≥ 2 per week for last 6 months	30-minute congruent Stroop task.	30 min MIST	HR Reaction time and accuracy during MIST	↑ HR ($p < 0.001$) CON: 62.0 ± 4.5 beats/min; INT: 65.8 ± 9.3 beats/min ↑ Reaction time ($p < 0.001$) ~ Response accuracy between condition ($p = 0.070$) or over time ($p = 0.507$)

Pires et al. (2018) Randomised counterbalanced design	**Recreational Cyclists** 8M, Age: 29.3 ± 7.9, 5.0 ± 3.2 years of experience	Sit comfortably for 30-minute	30-minute of rapid visual information processing test	EEG, Reaction time and accuracy during cognitive task	Within MF condition: ~ Reaction time ($p > 0.05$) ↓ Accuracy ($p = 0.04$, $\eta^2 = 0.22$): 10^{th} min: 11.5 ± 9.2% 20^{th} min: 11.4 ± 6.2% 30^{th} min: 15.5 ± 7.8% ↑ Fp1 theta band power ($p = 0.03$)
Roussey et al. (2018) Randomised counterbalanced design Randomised counterbalanced design	**Competitive cyclists and triathlon** 11M, Age: 27.0 ± 8.6, maximal aerobic power: 346 ± 56W, maximal oxygen uptake 63 ± 5mL.min-1.kg-1	Watching a 60-minute documentary	60 min MIST (experiment 1 & 2)	Average HR	~ HR ($p = 0.977$)
Rozand et al. (2014) Randomised counterbalanced design	**Active Individuals** 12M, Age: 24.5 ± 1.4	Watching a 27-minute documentary	27 min CST OR 27 min MIST	Average HR and response accuracy during task	↑ HR during the task ($p < 0.01$) except CON (69.5 ± 5.9 beats/min) CST: 80.3 ± 8.7 beats/ min ($p < 0.05$) MIST: 81.7 ± 9.7 beats/ min ($p < 0.05$) ~ Percentage of errors ($p = 0.093$) but MIST shows significantly higher errors compared to CST ($p < 0.001$)
Schucker and MacMahon (2016) – study 1 RCT	**Active Individuals** 3M9F, Age: 29.41 ± 14.47, 10 ± 7.35 years in team sport or endurance	10 min CST	10 min MIST	Average HR, mean RT and accuracy during MF protocol Glucose level	~ Average HR ($p = 0.1$) Slower RT ($p < 0.001$) CON 769.83 ± 175.89ms; INT 1498.58 ± 370.68ms ↓ Accuracy ($p < 0.001$) CON 98.73% ± 1.66; INT 83.55% ± 12.86 ~ Glucose levels
Schucker and MacMahon (2016) – study 2 RCT	**Active Individuals** 5M9F, Age: 30.64 ± 13.11, 14.54 ± 8.65 years in team sport or endurance training	Watching a 10-minute video	10 min MIST	Average HR, mean RT and accuracy during MF protocol	↑ Average HR ($p = 0.017$) CON: 66.0 ± 7.85; INT: 73.1 ± 8.49 RT: 1414.49 ± 207.57ms Percentage of response accuracy: 90.47 ± 9.2 %
Silva-Cavalcante et al. (2018) Randomised counterbalanced design	**Recreational Road Cyclists** 8M, Age: 33.8 ± 7.2, ~ 5 years of experience	Watching a 90-minute documentary	90 min AX-CPT	Knee extensors MVC	~ MVC ($p = 0.326$) ~ maximal voluntary activation level ($p = 0.823$) ~ twitch force ($p = 0.807$) ~ M-wave Amplitude ($p = 0.215$)

Smith et al. (2015) Randomised counterbalanced design	**Team Sport Players** 10M, Age: 22 ± 2, > 3 years of competition experience	Watching a 90-minute documentary	90 min AX-CPT	Average HR Response accuracy Blood glucose concentration	↑ Average HR ($p = 0.002$): CON: 62 ± 8 bpm; INT: 68 ± 9 bpm ↑ incorrect responses ($p = 0.018$): First 15 min: 2.4 ± 0.9 Final 15 min: 5.2 ± 3.1 ~ Blood glucose concentration ($p = 0.785$)
Slimani et al. (2018) Randomised counterbalanced crossover design	**Active Adolescents** 10M, Age: 16 ± 1.05, high school team sport athletes	30-minute of reading a magazine	30 min MIST (paper version)	Concentration performance and errors of d2 test after MF protocol	↓ Concentration performance ($p = 0.001$) ↑ Errors ($p < 0.001$)
Van Cutsem et al. (2019) Randomised crossover design	**Healthy** 5M6F, Age: 25 ± 4; not engaged in any kind of regular physical activity for last 5 years **Badminton player** 5M4F, Age: 23 ± 3; ≥8 years badminton experience	Watching a 90-minute documentary	90 min MIST	Eriksen Flanker task Visuomotor task Mean HR	Eriksen Flanker task: ~ Reaction time ~ Accuracy Visuomotor task: Complex stimuli: Slower response time in MF ($p < 0.001$, $d = 0.98$) PRE: 1282 ± 242ms POST: 1372 ± 249ms Badminton players has faster RT than healthy individuals ($p =0.022$, $\eta^2_p = 0.26$) before MIST ↑ Mean HR ($p = 0.008$): CON: 72 ± 9 bpm; INT: 77 ± 9 bpm
Verschueren et al. (2020) Randomised counterbalanced crossover design	**Recreational Active** 10M4F, Age: 22 ± 1, > 3 years of competition experience	Watching a 90-minute documentary	90-minute IST	Reaction time and accuracy during IST Eriksen Flanker task	Within MF condition: ~ Reaction time ~ Response accuracy Eriksen Flanker task: ↓ Accuracy ($p = 0.002$, $\eta^2 = 0.579$) ~ Reaction time
Vrijkotte et al. (2018) Randomised placebo-controlled crossover design	**Cyclists** 9M, Age: 26 ± 6, $VO_{2\ max}$ 61.67 ± 5.05 mL. kg. min	90-minute rest	90 min IST	Eriksen Flanker task Reaction time and response accuracy during IST	Within MF condition (6 x 15min blocks) ~ Reaction time between blocks (700.26 ± 68.82ms to 720.10 ± 61.26ms) ~ Response accuracy between blocks 65.22 ± 17.64% to 87.56 ± 14.5% Eriksen Flanker task: ~ RT ~ Accuracy

↑: increased significantly; ↓: reduced significantly; ~ : similar to no significant difference compared to CON; AX-CPT: AX Continuous Performance Test; CST: Congruent Stroop Task; F: Female; HR: Heart Rate; IST: Incongruent Stroop Task; M: Male; MF: Mental Fatigue; MIST: Modified Incongruent Stroop Task; RT: Reaction Time.

2.5.1.1 Reaction Time

Reaction time (RT) represents the neuromuscular coordination between brain and motor responses, and it refers to the length of time required to react to a stimulus (Kuhl et al., 2019). Changes in RT are frequently assessed in MF studies because MF has been proposed to negatively impair RT due to increased subjective feelings of tiredness and delays in decision-making (Van Cutsem et al., 2017; Habay et al., 2021). The effects of MF on RT were assessed in two ways, according to Table 2.5: during the MF intervention and before and immediately after the MF intervention. Based on these varied measurement approaches, the following sections will discuss the influence of MF on RT.

2.5.1.1.1 Reaction time during the MF intervention

Seven studies evaluated changes in RT between two different levels of the Stroop-color task (Boat et al., 2021a; Schucker et al., 2016; Gantois et al., 2019; Pageaux et al., 2014, Pageaux et al., 2015; MacMahon et al., 2019; Fairclough et al., 2004). Boat et al. (2021a) investigated 13 well-trained hockey players and discovered that RT in an incongruent Stroop test (IST) was significantly slower ($p < 0.001$) than in a congruent Stroop task (CST) over 4 minutes. Similarly, Schucker et al. (2016) found significant impairment ($p < 0.001$) in RT when comparing performance in a 10-minute modified incongruent Stroop task (MIST) to CST in 12 recreationally active individuals. MacMahon et al. (2019) also found that recreationally active individuals had slower mean RT ($p < 0.05$) and latency ($p < 0.001$, partial $\eta^2 = 0.72$) during a 30-minute IST compared to CST. Another investigation with 30 healthy individuals reported that a 45-minute IST resulted in a significantly slower RT ($p < 0.01$) than CST (Fairclough & Houston, 2004). However, the remaining investigations with recreationally active individuals employing a 10-minute (Schucker et al., 2016) or 30-minute CST and IST (Pageaux et al., 2014, Pageaux et al., 2015) did not show any significant changes in RT.

The main difference between CST and IST/MIST is that the colour in IST/MIST does not match the meaning of the word. Responding to the stimuli may require a higher level of attention and cognitive processing, which results in greater cognitive load. According to the findings presented, a more complicated MF protocol resulted in slower RT (Boat et al., 2021a; Schucker et al., 2016; MacMahon et al., 2019), showing that greater cognitive effort is needed during the MF intervention. Additionally, Gantois et al. (2019) assessed RT during IST in 20 professionally trained football players and discovered a significantly slower RT ($p = 0.03$) in a 30-minute IST compared to a 15-minute IST. This is the only study that evaluated the effects of MF on RT between two different durations of MF protocols with the same group of participants. Therefore, further investigation is needed to assess whether the extended duration of the MF intervention affects the extent of impairment in RT. Unlike the previous research, Gantois et al. (2019) did not employ a low-cognitive-demand activity, such as CST, as a control condition but instead selected a 30-minute video-watching session. It remains essential to determine whether the negative changes in RT are related to the duration of the MF intervention and to compare whether the delayed RT is exclusively attributed to task complexity or MF alone.

The nine included studies in Table 2.5 utilised video watching or resting as a control condition, and RT measurements were recorded only during the MF intervention condition (Filipas et al., 2018; Filipas et al., 2020; Pires et al., 2018; Martin et al., 2016; Kosack et al., 2020; Lopes et al., 2020; Martin et al., 2015; MacMahon et al., 2014; Verschueren et al., 2020). The comparison primarily focused on changes in RT during the MF intervention. For instance, Kosack et al. (2020) studied 19 trained badminton players and reported a significantly faster RT during a 60-minute IST. Similarly, Martin et al. (2016) reported a significant change in RT during a 30-minute MIST, with 11 trained cyclists showing a significantly faster RT ($p < 0.001$) and 9 recreational cyclists having a significantly slower RT ($p = 0.019$) during the same MF protocol. Conversely, the remaining studies using 30- (Filipas et al., 2020; Pires et al., 2018; Kunrath et al., 2020a), 45- (Lopes et al., 2020), 60- (Filipas et al., 2018) and 90-minute (Verschueren et al., 2020; Martin et al., 2015; MacMahon et al., 2014) MF protocol did not reveal significant changes in RT. However, determining whether the significant changes in RT are primarily due to the selection of the cognitively demanding task is difficult because the majority of studies reported insignificant findings also used MIST, IST, and other tasks such as the AX-CPT (Martin et al., 2014) and rapid visual information processing task (Pires et al., 2018). A primary limitation of these nine studies is that RT measurements were collected only during the MF protocol rather than before and after the MF protocol. The use of particular RT tests before and after the MF intervention is discussed in section 2.5.1.1.2. Furthermore, it is difficult to determine the precise effect of MF on RT when no RT measurement is included in the control condition. The interpretation of the results is further complicated by the broad variety of MF protocols used and the absence of an appropriate control group.

Most of the studies in Table 2.5 indicated slower or similar RT following the MF intervention; however, the two studies with well-trained individuals demonstrated an improvement in RT (Kosack et al., 2020; Martin et al., 2016). This could be attributed to the insufficient stress on the cognitive aspect in well-trained individuals (Borragán et al., 2017; Cona et al., 2015) or the repetitive nature of the MF intervention, where they may have been able to suppress the processing of irrelevant information (Cona et al., 2015). It is difficult to conclude whether MF influences RT when changes in RT are measured exclusively during the MF intervention without comparing them to a control condition. Implementing sport-specific RT tests could address potential differences between laboratory and sporting environments, leading to a better assessment of RT.

2.5.1.1.2 Reaction time test before and after MF protocol

Table 2.5 included five studies that assessed RT before and after the MF protocol. The Eriksen-Flanker task was used in four studies (Vrijkotte et al., 2018; Van Cutsem et al., 2019; Fortes et al., 2021; Fortes et al., 2021), while the Vienna Test System was used in one study (Kunrath et al., 2020a). In response to the Eriksen-Flanker task, no significant impairments in overall RT were found following a 90-minute MIST with recreationally active individuals and badminton players (Van Cutsem et al., 2019), recreational cyclists in a 90-minute IST (Vrijkotte et al., 2018) or competitive soccer players in a 30-minute MIST (Kunrath et al., 2020a). Similarly, two studies using the Stroop-color task as an RT measurement (Fortes et al., 2020; Fortes et al., 2021) reported significant increases in RT after 30 minutes of using social media on smartphones or playing video games in well-trained swimmers and boxers, respectively. Based on the limited evidence, the assessment of the effects of MF on RT using specific RT tests before and after MF protocols presented inconsistent results. However, following the MF intervention, RT was either unaffected or increased.

Aside from the Eriksen Flanker task used to assess the RT of the individuals (Van Cutsem et al., 2019; Verschueren et al., 2020; Vrijkotte et al., 2018), Van Cutsem et al. (2019) also employed a visuomotor task to assess the RT and revealed a large significant impairment in RT ($p < 0.001$, $d = 0.98$) following the MF intervention. As shown in Table 2.5, most of the MF protocols were performed for prolonged periods, and the impairment in RT may not be primarily attributed to increased cognitive load but could be influenced by the nature of the RT test. For example, in Van Cutsem et al. (2019), the visuomotor task required individuals to react to different stimuli while also involving body coordination, unlike the Eriksen-Flanker task and Stroop tasks. The findings suggest that MF may have a detrimental impact on cognitive performance, especially in decision-making tasks involving more complex situations. This is evident in the significant increase in both perceived MF and RT observed after the MF intervention in response to complex stimuli in visuomotor tasks, compared to the control condition. While an increase in RT has been recorded following MF intervention, it is unclear whether this impairment is due to more complex stimuli in the visuomotor task or the presence of MF. It is difficult to conclude that there will be a definite cognitive impairment in a sporting context since the cognitive demands of the visuomotor activity do not appropriately align with the cognitive demands in sports. As mentioned in section 2.5.1.1.1, future research should assess RT before and after the MF protocol instead of analysing fluctuations in RT throughout the MF intervention. This approach may reduce potential confounding variables and increase the validity of the findings by providing a direct comparison between control and MF conditions.

2.5.1.2 Response Accuracy

The response accuracy in this thesis is defined as the number of correct responses obtained during the task or test. Table 2.5 includes 29 studies that examined the changes in response accuracy during the MF intervention, including AX-CPT, N-back tests, rapid visual information processing tests, and congruent, incongruent and modified incongruent Stroop colour tasks. Despite the differences in the duration and type of the MF intervention, four different methods of analysing response accuracy were identified across these studies.

The first method compares the overall response accuracy of a less difficult task to a more complex MF intervention. Some studies reported a significant decline in response accuracy when comparing a 4-minute CST and an IST in 13 male national hockey players (Boat et al., 2021), as well as between a 10-minute CST and MIST in recreationally active individuals (Schucker et al., 2016). However, significant changes were not consistently observed in the other studies. For example, a study with 20 professional soccer players comparing a 15-minute IST to a 30-minute IST (Gantois et al., 2019), and another with 31 well-trained distance runners comparing a 45-minute combination of congruent and incongruent Stroop task (Lopes et al.,

2020) reported no differences in response accuracy between conditions. Additionally, the investigation with national-level soccer players using a 30-minute MIST with documentary watching as their control condition found no significant impairment in response accuracy across age groups (under 14s, under 16s and 18s)(Filipas et al., 2020). However, it is important to highlight that the significant changes observed may be attributed to the task differences, such as the mismatch of colour stimuli and word meaning in IST and MIST, which might naturally lead to decreased response accuracy in the absence of MF. Consequently, comparing overall response accuracy between two different MF intervention tasks may reflect task complexity rather than the presence of MF.

The majority of the studies in Table 2.5 employed the second data analysis approach, which examined response accuracy at different time frames throughout the MF intervention. Thirteen studies compared response accuracy at five different intervals: every 3 minutes (Rozand et al., 2014), 5 minutes (Martin et al., 2016; Pageaux et al., 2014; Pageaux et al., 2015; Holgado et al., 2019), 6 minutes (Kosack et al., 2020), 10 minutes (MacMahon et al., 2019; Brown et al., 2019; Filipas et al., 2018; Hachard et al., 2020; Pires et al., 2018) and 15 minutes (Vrijkotte et al., 2018; Fairclough et al., 2004) of the MF intervention. The influence of MF on the measured variable was hard to evaluate and compare when there was a lack of consistent measurement durations between investigations. Interestingly, 10-minute intervals were used in the majority of studies that reported a significant decrease in response accuracy. Furthermore, a 20-minute N-back test with 28 recreationally trained cyclists demonstrated a significant decline in response accuracy performance every 5 minutes (Holgado et al., 2019). Two studies reported a significant decline in response accuracy, suffering from a similar limitation as mentioned above, where the control condition was a simplified version of the MF protocol, such as 1-back test versus 2-back test (Holgado et al. 2019) and CST versus IST (MacMahon et al., 2019). While response accuracy may gradually decrease over time when performing the more difficult task, this did not necessarily represent the presence of MF.

The remaining studies reported a significant decline in response accuracy during a 30-minute rapid visual information processing task (Pires et al., 2018), 50- (Brown et al., 2019) and 90 min AX-CPT (Hachard et al., 2020) using a 10-minute time frame. Further investigation of the athletic population is needed, as all the studies that demonstrated significant findings used recreationally active individuals. Martin et al. (2016) also reported that despite no significant changes in response accuracy every 5 min during a 30-minute MIST, professional road cyclists in their study completed significantly more responses than recreational road cyclists, highlighting the importance of separating recreational and athletic populations for further investigation.

The third analysis method compared performance between the initial and final designated time intervals. Among the five studies in Table 2.5 utilizing this approach, only one study compared the first and final 3 minutes of response accuracy during AX-CPT and identified significant impairment (MacMahon et al., 2014), while four studies that used the first and final 15 min of the AX-CPT did not present any significant changes (Martin et al., 2015; Smith et al., 2015; Marcora et al., 2009; Holgado et al., 2020). Although all five studies employed AX-CPT as their MF protocol and recruited recreationally active individuals, the inconsistent findings could be attributed to the difference in the measurement timeframes. However, this analysis method has certain limitations. MF is believed to develop following an extended period of cognitively demanding tasks, meaning that MF evolves gradually (Van Cutsem et al., 2017). This approach might miss important information regarding the development of MF during the intervention. Furthermore, there is also a potential bias as the participants might be more attentive and alert at the beginning and end of the protocol, which may explain why most of the studies using this analysis method did not present significant changes in response accuracy.

Seven studies in Table 2.5 implemented specific cognitive tests to assess response accuracy before and after MF protocol, including the Stroop-colour task (Fortes et al., 2020; Fortes et al., 2021; Fortes et al., 2021), Eriksen Flanker task (Van Cutsem et al., 2019; Verschuerecen et al., 2020; Vrijkotte et al., 2018) and the D2 test (Slimani et al., 2018). Verschuerecen et al. (2020) was the only study that reported significant impairment, while no significant changes were found in the other studies that utilised similar levels of participants, cognitive tests, type and duration of MF protocols (Van Cutsem et al., 2019; Vrijkotte et al., 2018). However, the findings of Fortes et al. (2021) should be interpreted with caution as one of their experimental trials utilised a 60-minute Stroop-colour task as the MF protocol while using a 45-word Stroop task to assess cognitive function before and immediately after the intervention. The repeated administration of the same cognitive test may not reflect a genuine change in cognitive function, as there may be a practice effect following the MF protocol. Regardless of the type of test used in these studies, these tests lacked ecological validity and did not accurately reflect the complexity and demands of sports environments, indicating low generalizability of the results.

Collectively, the discussed evidence has heavily focused on changes in response accuracy within the MF condition rather than comparing it to a control condition, making it difficult to generate meaningful conclusions. Moreover, the discrepancy in the analysis methods and the duration of the MF protocol may further complicate the interpretation of the result. It is unclear whether the decrease in response accuracy is primarily attributed to MF due to the differences in experimental settings. This thesis acknowledges examining the response accuracy during computerised MF protocol may not accurately reflect the multi-dimensional construct of MF. The changes observed in laboratory-based experiments using this assessment method may suffer from low ecological validity. Importantly, it is encouraged to standardise the cognitive tests and measurement timeframes to increase the comparability of findings. It may be more meaningful for future research to employ specific cognitive tests such as the Eriksen Flanker task or a 30-word Stroop task as behavioural indicators to evaluate changes in response accuracy before and after MF interventions.

2.5.1.3 Blood Glucose Level

While some studies have suggested a link between MF and blood glucose levels (Gailliot, 2008; Gailliot et al., 2007), the included studies in Table 2.5 showed inconsistencies in the changes in blood glucose following MF intervention. One potential mechanism is that increased activity in the prefrontal cortex could enhance blood glucose uptake, potentially resulting in lower blood glucose concentrations (Martin et al., 2018). However, this explanation appears oversimplified and lacks comprehensive support from the available evidence. While variability in blood glucose changes following the MF intervention was observed (Marcora et al., 2009; Pageaux et al., 2014), glucose utilisation in the brain is a complex process that may be influenced by other factors. The results were conflicting because some studies reported a gradual decrease in glucose levels over time with no significant differences between control and MF conditions (Marcora et al., 2009; Pageaux et al., 2014). In these studies, blood glucose levels were not significantly affected following the mental exertion task. Another point of criticism was the ineffectiveness of glucose supplementation in restoring performance in mentally fatigued individuals (Boat, Taylor, & Hulston, 2017b). These findings indicated that the influence of blood glucose on MF may be more complex than previously stated, raising concerns about the sensitivity of blood glucose as a measure of MF.

An important consideration is that only one of the six studies listed in Table 2.5 reported dietary control before the experiment (Schucker et al., 2016). This indicated that the lack of standardised dietary control may have influenced baseline glucose levels and, consequently, the outcomes. Despite this control measure, blood glucose levels remained unchanged after a 10-minute mental exertion task (Schucker et al., 2016), raising questions about the efficacy of blood glucose as a reliable indicator of MF. Furthermore, the included studies measured peripheral blood glucose, which may not accurately reflect brain metabolism. However, it is technically impossible and unethical to employ invasive methods for directly measuring brain tissues in humans to validate this hypothesis. Additionally, blood glucose was only evaluated during isolated cognitively demanding activities in the included studies, with no physical stress involved. This may not accurately reflect the sports environment, which includes both cognitive and physical demands. Given that depletion of muscle glycogen occurs naturally during exercise (Gailliot, 2008), examining the effects of both cognitive and physical stress on glucose levels may complicate identifying the primary causes of changes in glucose levels. Given these limitations, the practicality of using blood glucose as an MF indicator, particularly in the context of sports remains unclear.

2.5.1.4 Heart Rate

Out of the 11 studies included in Table 2.5 that measured mean HR during mental exertion tasks, eight studies reported a significant increase ($p < 0.05$) (Van Cutsem et al., 2019; Smith et al., 2015; Marcora et al., 2009; Pageaux et al., 2015; Clark et al., 2019; Batista et al., 2021; Rozand et al., 2014; Schucker et al., 2016), while the remaining studies did not report significant changes ($p > 0.05$) between control and experimental conditions (Brown & Bray, 2019; Roussey et al., 2018; Schücker & Macmahon, 2016). Among the studies reporting significant increases in mean HR during the MF protocol, the variation in control conditions and MF tasks made it difficult to determine whether the observed changes in HR were attributed to MF or simply a result of increased arousal due to engagement in the experimental task. For example, Schucker et al. (2016) with 11 recreationally active individuals showed a significant increase ($p = 0.017$, $d = 0.86$) in mean HR during a 10-minute MIST compared to watching a 10-minute emotionally neutral video. However, the study by Schucker et al. (2016) with 12 recreationally active individuals using a 10-minute low cognitive demand task as a control condition did not report any significant change ($p = 0.10$) in mean HR. This discrepancy in findings undermined the reliability of HR as a consistent measure and indicator of MF. Clark et al. (2019) reported that insignificant changes in mean HR could be attributed to the training status of the individuals, as the trained population may have a more stable mean HR compared to the untrained population during the MF protocol. However, another study with recreationally active individuals also demonstrated no change in HR in the presence of MF (Schücker & Macmahon, 2016), contradicting the explanation that training status can influence HR responses during an MF intervention. Additionally, in studies involving recreationally active individuals, there were no significant changes in mean HR when watching a 50-minute ($p = 0.45$, $d = 0.14$) documentary (Brown & Bray, 2019) or a 60-minute ($p = 0.977$) documentary (Roussey et al., 2018) compared to AX-CPT or MIST. These findings suggest that HR may not be sensitive enough to detect MF in individuals with varying training levels. Another plausible explanation is that the measurement of HR was not primarily used to assess MF but rather to monitor changes in HR before subsequent exercise tasks

In conclusion, while there is a possibility that individuals may exhibit higher mean HR during isolated cognitively demanding tasks, the evidence that exclusively examines the relationship between HR and changes in other subjective and objective measurements of MF is insufficient. Therefore, HR cannot be considered a reliable indicator of MF.

2.5.1.5 Brain Wave Activity

Electroencephalography (EEG) and functional magnetic resonance imaging have been used to investigate brain wave activity and evaluate the impact of MF (Brownsberger et al., 2013; Hotama et al., 2017; Pires et al., 2018; Sun et al., 2014; Taya et al., 2018). During MF interventions, previous research has found greater activation in the prefrontal cortex, particularly the ACC and dorsolateral prefrontal cortex, as well as an increase in subjective feelings of MF (Hotama et al., 2017; Pires et al., 2018; Sun et al., 2014; Taya et al., 2018). However, it is crucial to emphasise the interpretation of prefrontal brain activity as a result of MF may be oversimplified. A previous systematic review found that MF influenced brain wave activity in several brain areas, including the frontal, central, and posterior brain regions (Tran et al., 2020).

This suggests that MF may have a broader influence on brain function than previously recognised. Furthermore, the relationship between EEG changes and MF is not fully understood. Changes in theta and alpha bands of the spectral EEG have been shown to be closely linked to the development of MF (Tran et al., 2020). However, the underlying mechanism behind these changes and their specific implications for MF remain uncertain. Moreover, Pires et al. (2018) is the only study examining EEG changes during a 30-minute rapid visual information processing test and a subsequent 20km cycling TT. This study found significantly higher ($p = 0.03$) and large changes ($\eta^2 = 0.3$) in EEG theta band power during cognitively demanding tasks in eight recreational male cyclists compared to the control condition. During the 20km TT, the higher EEG theta band power remained elevated ($p = 0.01$) with a large effect size ($\eta^2 = 0.29$). While this suggests a potential link between EEG changes and MF, the small sample sizes may limit the generalisability of the findings. It is also important to consider that increased prefrontal cortex activation observed during the MF intervention did not further increase during the subsequent 20km TT, nor did it impair power output. It is possible to conclude that higher EEG activity may indicate the presence of MF but not necessarily reflect how significantly it may impair subsequent performance.

Previous research has found that declined mental performance including situation awareness and reaction time is related to increased power in brain wave activity, particularly in the 4 to 13 Hz bands (Borghini et al., 2014; Kiroy, Warsawskaya, & Voynov, 1996). A meta-analysis supported this finding, indicating MF increased slow wave EEG activity in the 4-13 Hz frequency range, specifically in theta and alpha bands (Tran et al., 2020). Moreover, mentally fatigued individuals demonstrated increased theta band activity in the prefrontal cortex during subsequent endurance cycling exercise (Pires et al., 2018), aligning with the conclusions of a previous systematic review (Tran et al., 2020) and research on EEG changes under a mentally fatigued state (Borghini et al., 2014; Fonseca et al., 2018). However, it is important to note that some studies measured brainwave activity during simulated driving tasks, which are more complex and ecologically valid than computerised cognitively demanding tasks (Borghini et al., 2014; Fonseca et al., 2018). The findings of this research provide important information about the efficacy of employing EEG as an indicator of MF. Regardless of the stimuli, Pires et al. (2018) found a similar increase in theta brain wave activity for both computerised cognitive tasks and subsequent endurance tests. While measuring theta wave activity with EEG appears to be effective in identifying the presence of MF, the results should be interpreted with caution. Significant decreases in theta and alpha band activity during sustained attention activities may indicate MF or attention loss. It is also necessary to examine other variables that may affect brain wave activity, such as motivation and emotional state.

As concluded above, future investigations should prioritise monitoring theta wave activity via EEG to assist in recognising the development of MF, while also considering alpha wave activity as a secondary resource to address individual variability (Tran et al., 2020). However, further investigation is needed to understand the role of delta and beta wave activity concerning MF. It is important to note that the mechanism of MF has not been fully elucidated, making it questionable whether increased brain wave activity can be directly interpreted as the development of MF. While EEG implementation holds the potential for explaining the development of MF, the increased brain wave activity may only represent the amount of cognitive effort invested in the task, rather than the presence of MF. Therefore, brain wave activity should not be utilised as the only indicator or measurement of MF. The practicality of implementing EEG to objectively measure MF in an elite sporting environment is limited due to the turbulence associated with whole-body exercises, which may affect the accuracy of the findings (Pires et al., 2018; Thompson et al., 2008; Monteiro et al., 2019). Another major concern when using EEG as a measure of MF is the cost of EEG equipment and the need for specialist personnel to operate it, which is relatively inaccessible to the majority of the population. Further research is required to improve the feasibility of implementing EEG in an elite sports environment before further discussing its effectiveness in identifying MF.

2.5.1.6 Recommendations

In summary, this thesis concludes that identifying an ideal objective measurement for MF is challenging due to technological limitations and the complex nature of MF in sports. One major drawback of objective measuring tools is that MF is a subjective feeling of tiredness following a prolonged period of cognitive activity (Van Cutsem et al., 2017). To elaborate, MF is a subjective state and the perception of MF may vary between individuals. The changes in objective measures under the MF state may not fully reflect the extent of MF experienced by individuals or explain the impact of MF on subjective responses. While MF can lead to impairments in subsequent physical performance (Giboin & Wolff, 2019; Habay et al., 2021; Van Cutsem et al., 2017), the underlying mechanism of MF remains unclear, making it difficult to objectively measure MF. Although a recent review showed that the performance level of individuals does not affect MF susceptibility (Habay et al., 2023), there is evidence showing individuals with different training statuses (Martin et al., 2016) and occupations (Martin et al., 2019) demonstrated better resistance to MF. This further complicates the selection of an appropriate objective MF measuring tool.

Indeed, every objective measurement tool has its limitations. Although monitoring brain wave activity seems to be a viable option for objective measurement, increased brain wave activity only indicates higher activation during or after cognitively demanding tasks and does not necessarily validate the presence of MF. Additionally, measuring brain wave activity in theta and alpha bands may be useful to evaluate the effectiveness of the MF protocol in challenging one's cognitive output, but not for validating the presence of MF. Furthermore, while objective measures such as monitoring brain wave activity can provide information about neural activation during the MF protocol, they may not be practical due to the specialised equipment and expertise required as specified in section 2.5.1.5. Given the limitations of monitoring brain wave activity, as detailed in section 2.5.1.5, and the discussions from sections 2.5.1.1 to 2.5.1.5, incorporating sport-specific tests may emerge as a viable option for evaluating the effects of MF. However, it is crucial to acknowledge that the objective measurements discussed for MF exhibit varying degrees of limitation. Consequently, this thesis cannot conclusively determine which objective indicator may serve as a superior measure of MF.

Although previous reviews have concluded that engaging in an MF protocol negatively affects subsequent RT and response accuracy (Sun et al., 2020; Habay et al., 2023; Kunrath et al., 2020b), it may be more convincing to use sport-specific tasks that align with participants' characteristics and real-world situations, rather than generic cognitive tests like the Eriken Flanker test and Stroop-colour task. For instance, utilizing the Loughborough soccer shooting and passing test for soccer players could better reflect the decision-making and cognitive demands encountered in soccer. However, sections 2.5.1.1 and 2.5.1.2 emphasise the inconsistency and inadequacy in the measurement of RT and response accuracy in the literature. Therefore, standardising objective measures of MF across all studies, along with a study-specific measure, is crucial to increasing the comparability of results. Without this standardisation, selecting the most appropriate assessment tools for further investigation becomes more challenging.

2.5.2 Subjective Measurement

A variety of subjective measurements have been employed to quantify MF in the literature. This section provides a critical discussion of the most common of those measurements, and the evidence discussed is summarised in Table 2.6.

Table 2.6 Overview of the subjective mental fatigue measurement (review articles are excluded, n = 54)

Study	Participant (Characteristics, number, age, training history)	Control condition	Induction method	Subjective measurement	Outcome (CON vs INT)
Alder et al. 2021 Randomised counterbalanced design	**Soccer players** 16M, Age: 22.4 ± 2.5, 14 ± 3.6 years of experience in soccer, Average training hours: 3750 ± 423, Average played competitive matches: 340 ± 13.2	20 min anticipation test film (verbally anticipate the action of the ball carrier of a 11 vs 11 soccer match)	30min incongruent Stroop task	Rating scale of mental effort (0 to 150)	↑ Mental effort ($p < 0.01$) CON: 32.83 ± 11.34; INT: 43.08 ± 10.67
Badin et al. (2016) Randomised crossover design	**Soccer Players** 20M, Age: 17.8 ± 1.0; 8.3 ± 1.4 year of experience in competition	Watching a 30-minute documentary	30 min mixture of congruent and incongruent Stroop task	100-mm VAS (MF, Mental effort)	↑ MF (ES = 0.95 ± 0.36) CON: ES = 0.38 ± 0.36; INT: ES = 1.50 ± 0.47 ↑ Mental effort (ES = 1.34 ± 0.54) CON: 33 ± 23; INT: 63 ± 20
Boat and Taylor (2017a) Counterbalanced design	**Healthy** 21M42F, Age: 22 ± 3, trained 4 ± 2 days per week	4-minute congruent Stroop task	4 min MIST	Daily Inventory of Stressful Events Questionnaire POMS (fatigue) McGill pain questionnaire Borg's CR-10 scale – mental exertion	Borg's CR-10 scale: ↑ Mental exertion ($p < 0.001$) ~ Daily Inventory of Stressful Events Questionnaire ($p = 0.024$) POMS: ~ ratings of physical fatigue ($p = 0.74$)
Boat et al. (2020) Counterbalanced design	**Healthy** 11M18F, Age: 20.7 ± 0.8, exercised 3 ± 2 days per week	4-minute congruent Stroop task	4, 8 and 16 min IST	Borg's CR-10 scale – mental exertion 100-mm VAS: Motivation	Borg's CR-10 scale: ↑ Mental exertion except CON ($p < 0.001$) CON: 0.8 ± 0.1 4-min: 2.5 ± 0.2 8-min: 3.9 ± 0.3 16-min: 5.5 ± 0.4 100-mm VAS: ↓ Motivation 4-min ($p = 0.007$) 8-min ($p = 0.037$) 16-min ($p = 0.008$)
Boat et al. (2021a)	**Hockey players** 13M, Age 20 ± 1, competing in national or regional leagues	4 min Congruent Stroop task	4 min IST	POMS: Fatigue Borg CR-10 scale: Mental exertion	POMS: ~ Fatigue ($p = 0.104$) Borg CR-10 Scale: ↑ Mental exertion ($p = 0.005$)

Randomised counterbalanced crossover design					INT: 4.2 ± 1.4 CON: 2.8 ± 1.4
Brown and Bray (2019) Randomised crossover design	**University students** 13M12F, Age: 20.16 ± 1.48, involved in physical activity: 92.13 ± 44.24 min per week	Watching a 50-minute documentary	50 min AX-CPT	100-mmVAS: MF	100-mm VAS ↑ MF (p = 0.001)
Brown et al. (2021) Randomised crossover design	**Recreationally active individuals** 10M, Age: 22 ± 3, mean weight of one repetition maximum in biceps curl: 45.91 ± 4.55kg, > 1 year of resistance training experience	Watching a 10-minute documentary	10 min incongruent Stroop task	100-mm VAS: MF Task motivation	100-mm VAS: ~ MF (p = 0.78) ~ Task motivation (p = 0.67)
Campos et al. (2019) Randomised counterbalanced design	**Judo Players** 9M4W, Age: 19.5 ± 3.0, 7.2 ± 3.9 years of experience	Watching a 30-minute documentary	30 min MIST (paper version)	100-mm VAS MF, Mental effort	↑ MF (p = 0.04) INT: 45.7 ± 19.0 CON: 22.3 ± 23.0 ↑ Mental Effort (p < 0.001) INT: 63.2 ± 21.0 CON: 21.4 ± 20.9
Clark et al. (2019) Randomised crossover design	**Untrained** 10M, Age: 25.8 ± 4.6, Trained < 3 hours/week **Trained** 10M, Age: 27.4 ± 6.3, Trained > 9.5 hour/week	Watching a 30-minute documentary	30-minute N-back task and a mixture of congruent and incongruent Stroop colour task (alternated on a 2- and 3-min loop)	Untrained: ↓ positive affect ~ negative affect Trained: ↓ positive affect ↑ negative affect	Untrained: ↓ positive affect ↑ negative affect (p = 0.012) Trained: ↓ positive affect (p = 0.033) ↑ negative affect
Coutinho et al. (2017) Randomised counterbalanced crossover design	**Youth Soccer Players** 12M, Age: 15.9 ± 0.8, 8.9 ± 2.4 years of experience in soccer	20 min light aerobic exercise	20 min whole-body coordination task	100-mm VAS: MF	100-mm VAS: INT: ↑ MF by 537% (p = 0.001) CON: ↑ MF by 57% (p = 0.025)
Coutinho et al. (2018) Randomised counterbalanced design	**Soccer Players** 10M, Age: 13.7 ± 0.5, 6.1 ± 0.9 years of experience, from Portugal regional soccer academy	N/A	30 min MIST	100-mm VAS: MF	100-mm VAS: ↑ MF (Magnitude-based inference: moderate effect, 1.0 ± 0.4)

Faro et al. (2020) Randomised counterbalanced design	**National Basketball Players** 14M, Age: 24.3 ± 4.1, 6.5 ± 1.9 years competitive experience in second division of National League of Brazil	Watching 60 min documentary	60 min basketball-based video game on PlayStation 4	100-mm VAS: MF, Motivation	100-mm VAS: ↑ MF ($p = 0.001$) CON: 16.18 ± 5.59; INT: 54.23 ± 14.75 ~ Motivation ($p = 0.46$) CON: 92.12 ± 5.02; INT: 94.35 ± 4.96
Filipas et al. (2018) Randomisesd counterbalanced crossover design	**Youth Rowers** 11M6F, Age: 11 ± 1.06, > 2 training session per week in local club	60-minute drawing task with grey pencil	INT1: 60 min MIST INT2: 60-minute arithmetic test	BRUMS: Vigour, Fatigue NASA-TLX: Effort, Mental demand, Temporal demand	INT1 vs CON: Temporal demand ($p = 0.009$) INT2 vs CON: Effort ($p < 0.001$); Temporal demand ($p = 0.214$); Mental demand ($p < 0.001$); Frustration ($p = 0.001$); physical demand ($p = 0.158$) INT1 vs INT2: Frustration and mental demand ($p = 1.000$); Effort ($p = 0.527$); temporal demand ($p = 0.922$); physical demand ($p = 0.229$) BRUMS CON vs INT1: fatigue ($p = 0.437$); vigour ($p = 0.143$) CON vs INT2: fatigue ($p = 0.197$); vigour ($p =1.00$) INT1 vs INT2: fatigue ($p = 0.100$); vigour ($p = 0.197$)
Filipas et al. (2019) Randomised counterbalanced crossover design	**Road cyclist** 10M, Age: 20.0 ± 1.2, > 3 years of experience	Watching a 30-minute video	30 MIST	BRUMS: Fatigue, Vigour NASA-TLX: Effort, Mental demand, Temporal demand, Performance demand, Physical demand, Frustration	BRUMS: ↓ Vigour ($p = 0.018$) ↑ Fatigue ($p = 0.002$) NASA-TLX: ↑ Mental demand ($p < 0.001$), Temporal demand ($p < 0.001$), Effort ($p < 0.001$), Frustration ($p < 0.001$) ~ Physical demand ($p = 0.56$) ~ Performance ($p = 1.00$)
Filipas et al. (2020) Randomised counterbalanced design	**Soccer Players** 12 from U14; 12 from U16; 12 from U18; > 3 years of experience in competing at national level	15-minute reading an emotionally neutral online magazine	30 min MIST	NASA-TLX: Effort, Mental demand, Temporal demand, Physical demand, Frustration	NASA-TLX: ↑ Effort (U14, U16, U18: $p < 0.001$) ↑ Mental demand (U14, U16, U18: $p < 0.001$) ↑ Temporal demand (U14, U16, U18: $p < 0.001$) ~ Physical demand (U14, U16,U18: $p > 0.05$) ↑ Frustration (U14, U18: $p < 0.001$; U16: $p < 0.01$)
Fortes et al. (2020)	**Professional Swimmers** 14M11F, Age: 20.4 ± 2.06, 8.4 years of experience in	Watching a 30 min coaching videos	30 min usage of social media application	100-mm VAS MF	100-mm VAS: ↑ MF ($p = 0.01$, $\eta^2 = 0.8$)

Randomised crossover design	international and national level swimming competition		(WhatsApp, Facebook and Instagram) on smartphone		
Fortes et al. (2021) Randomised crossover design	**Regional to national level boxers** 13M8F, Age: 23.33 ± 3.46, 8.9 years of experience in national and regional tournaments	Watching a 30 min coaching videos	30 min usage of social media application (WhatsApp, Facebook and Instagram) OR 30 min playing video games	100-mm VAS: MF	100-mm VAS: ↑ MF ($p = 0.001$)
Gantois et al. (2021) Randomised counterbalanced design	**Recreationally active individuals** 8M8F, Age: 24.8 ± 4.2, mean weight of 15 repetition maximum in back squat 75.2 ± 20.3kg, 1 to 5 years of resistance training experience	Watching a 30-minute advertising video	30 min smartphone	100-mm VAS: MF	100-mm VAS: ↑ MF ($p = 0.004$)
Gattoni et al. (2021) RCT	**Amateur long-distance runners** **46M,** Age: 43.8 ± 8.6, VO2 peak 46.0 ± 4.1 ml/kg/min, participated in marathon or half-marathon event during 2015-2017 held by Run4Science	50-minute of reading a magazine	50 min simple response task	NASA-TLX: Effort, Mental demand, Temporal demand, Performance, Physical demand, Frustration MF Physical fatigue Intrinsic motivation and success motivation scales	NASA-TLX: ↑ Effort ($p = 0.027$), Mental demand ($p = 0.053$), Temporal demand ($p < 0.001$) ~ Performance, Physical demand, Frustration ↑ MF ($p = 0.012$) ~ Physical fatigue ($p = 0.662$) Intrinsic motivation and success motivation scales: ~ Intrinsic motivation ($p = 0.919$) ~ Success motivation ($p = 0.713$)
Graham et al. (2017) Single-blind randomised design	**University students** 21M29W, Age: 20.98 ± 2.83	5-minute congruent Stroop task	5 min MIST	Borgs 10-point scale: Perceived mental exertion & physical exertion 5-point Likert scale: Brief Self-Control Scale 7-point Likert scale: Intrinsic Motivation Inventory; Mood Introspection Scale; State	Borg's 10-point scale: ↑ Perceived mental exertion ($p < 0.001$) ~ perceived physical exertion ($p > 0.05$) 5-point Likert scale: ~ Brief Self-Control ($p = 0.96$) 7-point Likert scale: ~ Intrinsic Motivation Inventory ($p > 0.05$) ~ Mood Introspection Scale ($p > 0.05$) Lower State Self-Control Capacity Scale Scores ($p = 0.02$)

				Self-Control Capacity Scale	Lower efficacy scores in bench press (p = 0.002) and leg extension (p = 0.014)
Hachard et al. (2020) Randomised crossover design	**Health individuals** 13M7W, Age: 21.8 ± 1.7	Watching a 90-minute documentary	90 min AX-CPT	NASA-TLX: Effort, Mental demand, Temporal demand, Performance, Physical demand, Frustration	NASA-TLX: ↑ Effort ($p < 0.01$), Mental demand ($p < 0.01$), Temporal demand ($p < 0.01$), Physical demand ($p < 0.01$), Frustration ($p < 0.01$) ~ Performance
Holgado et al. (2019) Randomised counterbalanced design	**Cyclists** 28M, Age: 27.0 ± 7.4, trained > 6 hour per week	20 min 1-back test	20 min 2-back test	100-mm VAS: MF	100-mm VAS: ↑ MF
Holgado et al. (2020) Randomised counterbalanced design	**Reactional Active** 24M6F, Age: 23.5 ± 6.3, Trained > 6 hour per week	Watching a 90-minute documentary	90 min AX-CPT	100-mm VAS: MF, Physical fatigue BRUMS: Fatigue, Vigour	100-mm VAS: ↑ MF, Physical fatigue BRUMS: ↑ Fatigue ↓ Vigour
Kunrath et al. (2020a) Non-randomised controlled design	**Soccer Players** 18M, Age: 21.8 ± 2.5, participated in national and state league tournaments	Watching a 30 min documentary	30 min MIST	100-mm VAS: Perception of MF	100-mm VAS: ↑ Perception of MF ($p < 0.001$) Pre INT: 22.2 ± 12.3 Post INT: 64 ± 17.9
Kosack et al. (2020) Randomised crossover design	**Elite Badminton Players** 19M, Age: 20 ± 2.8; 12.5 ± 3.5 years of experience with top 100 national Danish ranking	Watching a 60-minute documentary	60 min MIST	100-mm VAS: MF, Motivation, Focus	100-mm VAS: ↑ MF (p = 0.002) CON: 35 ± 21 vs 37 ± 23; INT: 32 ± 26 vs 57 ± 23 ~ Motivation, Focus
Lam et al. (2021) Randomised crossover design	**Reactional Active** Study 1: 9M, Age: 22 ± 2.6, recreationally active in variety of sport and exercise Study 2: 7M2F, Age: 21.1 ± 1.2, reactional runners	Study 1: N/A Study 2: N/A	30 min MIST	100-mm VAS: MF BRUMS: Fatigue, Vigour	Study 1: After INT 100-mm VAS: ↑ MF (unbiased d = 2.01, 95%CI 0.75 to 0.84) BRUMS: ↑ Fatigue (unbiased d = 2.55) ↓ Vigour (unbiased d = -1.90, 95%CL -0.72 to -3.43) Study 2: After INT 100-mm VAS ↑ MF (unbiased d = 1.44, 95%CI 0.67 to 2.5) BRUMS:

					↑ Fatigue (unbiased d = 0.67, 95%CI 0.07 to 1.38) ↓ Vigour (unbiased d = -0.99, 95%CL -0.45 to -1.73)
Le Mansec et al. (2018) Randomised controlled crossover design	**National Table Tennis Players** 22M, Age: 26.9 ± 8.9, competing at regional to national level	Watching a 90-minute movie	90-minute AX-CPT	100-mm VAS: Fatigue NASA-TLX: Effort, Mental demand, Temporal demand	100-mm VAS: ↑ Fatigue (p = 0.001) CON: 22.3 ± 17.7 vs 22.3 ± 16.2; INT: 14.7 ± 11.6 vs 55.9 ± 24.5 NASA-TLX: ↑ Mental demand (p < 0.001); physical demand (p < 0.001); temporal demand (p < 0.001); performance (p = 0.002); effort (p < 0.001)
Lopes et al. (2020) Randomised controlled crossover design	**Mid- and Long-Distance Runners** 16 Men, Age: 25 ± 1, weekly training distance: 96 ± 9 km 15 Women, Age: 25 ± 1, Weekly training distance: 88 ± 7 km	Watching a 45-minute documentary	45 min mixture of congruent and incongruent Stroop task	100-mm VAS: Mental effort, MF BRUMS: Fatigue, Vigour	100-mm VAS: ↑ Mental effort (p < 0.001), MF (p = 0.018) Men CON: 16 ± 4 vs 43 ± 6; INT: 17 ± 4 vs 58 ± 6 Women CON: 23 ± 4 vs 53 ± 6; INT: 25 ± 4 vs 68 ± 6 BRUMS ↑ Fatigue (p = 0.119) ↓ Vigour (p = 0.341)
MacMahon et al. (2014) Randomised counterbalanced design	**Recreational Active** 18M2F, Age: 25.4 ± 3.24, Trained 2.84 ± 1.79 hour/week	6-minute AXCPT & 84-minute documentary	90 min AX-CPT	POMS: Fatigue	POMS: ↑ Fatigue (p = 0.008)
MacMahon et al. (2019) Randomised counterbalanced design	**Active individuals** 10M3F, Age: 19.92 ± 1.75, 10.8 ± 4.48 years of playing experience	30-minute congruent Stroop task	30 min IST	7-point scale: Cognitive fatigue Perceived level of effort	7-point scale: ↑ Cognitive fatigue (p < 0.01) ↑ Perceived level of effort (p < 0.001)
Martin et al. (2015) Randomised crossover design	**Triathletes** 7M5F, Age: 23 ± 3, participate high-intensity training ≥ 3 time a week	Watching a 90-minute documentary	90 min AX-CPT	POMS: Fatigue, Vigour	POMS: ~ Fatigue (p = 0.358, η^2_p = 0.077), Vigour (p = 0.385, η^2_p = 0.069)
Martin et al. (2016) Randomised crossover design	**Professional Road Cyclists** 11M**,** Age: 23.4 ± 6.4, > 5 years of cycling experience	Sit quietly and focus on a black cross for 10-minute	30 min MIST	Four-Dimensional Mood Scale (4DMS): Relaxation Tiredness	4DMS: ↓ positive energy (p < 0.001), relaxation (p = 0.014) ↑ Increase tiredness (p < 0.001)

	Recreational Road Cyclists 9M, Age: 25.6 ± 5.3, ~2 years of cycling experience			~ Negative arousal NASA-TLX: Effort, Frustrating, Mental demand, Temporal demand	~ negative arousal, motivation NASA-TLX: Mental demand ($p < 0.001$), Temporal demand ($p < 0.001$), Frustrating ($p < 0.001$), Effort ($p = 0.033$) Professional rated MIST more effort than CON ($p = 0.001$); Recreational rated CON more effort than MIST ($p = 0.046$)
Martin et al. (2019) Randomised crossover design	**Untrained and Recreational Active** 8M15F, Age: 26 ± 6	Watching a 90-minute documentary	90 min MIST	100-mm VAS: MF NASA-TLX: Effort, Mental demand , Physical demand, Frustration	100-mm VAS: ↑ fatigue ($p = 0.001$) CON: 31 ± 21 vs 31 ± 20 INT: 31 ± 18 vs 48 ± 22 NASA-TLX: ↑ Effort ($p < 0.001$), Mental demand ($p = 0.004$), Frustration ($p < 0.001$) ~ Physical demand ($p = 0.618$)
Marcora et al. (2009) Randomised crossover design	**Recreational Active** 10M6F, Age: 26 ± 3	Watching a 90-minute of emotionally neutral documentary	90 min AX-CPT	BRUMS: Fatigue, Vigour	BRUMS: ↑ Fatigue ($p = 0.005$) ↓ Vigour ($p < 0.001$)
Pageaux et al. (2014) Randomised crossover design	**Recreational Active** 8M4F, Age: 21 ± 1, Trained ≥ 2 per week for last 6 months	30-minute congruent Stroop task.	30 min IST	BRUMS: Fatigue, Vigour NASA-TLX: Effort, Mental demand, Temporal demand	BRUMS: ↑ Fatigue ($p = 0.888$) ↓ Vigour ($p = 0.028$) NASA-TLX: ↑ Effort ($p = 0.009$), Mental demand ($p = 0.042$) ~ Temporal demand, Performance, Frustration
Pageaux et al. (2015) Randomised counterbalanced design	**Recreational Active** 12M, Age: 25 ± 4, Trained ≥ 2 per week for last 6 months	30-minute congruent Stroop task.	30 min MIST	BRUMS: Fatigue, Vigour NASA-TLX: Effort, Mental demand, Temporal demand	BRUMS: ~ Fatigue ($p = 0.369$), Vigour ($p = 1.000$) NASA-TLX: ↑ Effort ($p = 0.022$), Mental demand ($p = 0.012$), Temporal demand ($p = 0.050$) ~ Performance, Physical demand, Frustration
Penna et al. (2018a) Randomised crossover design	**Regional-level Handball Players** 12M, Age: 17.5 ± 3.6; 5 ± 2.2 years of experience	Watching a 30-minute documentary	30 min MIST (paper version)	100-mm VAS MF, Mental effort	100-mm VAS: ↑ MF ($p < 0.01$), Mental effort ($p < 0.001$)

Penna et al. (2018b) Randomised crossover desing	**Youth Swimmers** 11M5F, Age: 15.45 ± 0.51; 7.35 ± 2.20 years of experience with average training distance 30,000m/week	Watching a 30-minute emotionally neutral documentary	30 min MIST (paper version)	100-mm VAS: MF, Mental effort	100-mm VAS: ↑ MF ($p < 0.001$, d = 1.8), Mental effort ($p < 0.001$, d = 2.11)
Pires et al. (2018) Randomised counterbalanced design	**Recreational Cyclists** 8M, Age: 29.3 ± 7.9, 5.0 ± 3.2 years of experience	Sit comfortably for 30-minute	30-minute of rapid visual information processing test	Negative affect Positive affect POMS: Anger, Depression, Fatigue, Tension, Mental confusion, Vigour	↑ Negative affect ($p = 0.03$, extremely large ES) ↓ Positive affect ($p = 0.02$, extremely large ES) POMS: ↑ Tension ($p = 0.03$, extremely large ES), Mental confusion ($p = 0.02$, extremely large ES) ~ Depression ($p > 0.05$), Anger ($p > 0.05$), Fatigue ($p > 0.05$) ↓ Vigour ($p = 0.01$, extremely large ES)
Roussey et al. (2018) Randomised counterbalanced design	**Competitive cyclists and triathlon** 11M, Age: 27.0 ± 8.6, maximal aerobic power: 346 ± 56W, maximal oxygen uptake 63 ± 5mL.min-1.kg-1	Watching a 60-minute documentary	60 min MIST	BRUMS: Fatigue, Vigour NASA-TLX: Effort, Mental demand	BRUMS: ~ Fatigue ($p = 0.768$), Vigour ($p = 0.86$) NASA-TLX: ↑ Effort ($p = 0.002$), Mental demand ($p < 0.001$)
Rozand et al. (2014) Randomised counterbalanced design	**Active Individuals** 12M, Age: 24.5 ± 1.4	Watching a 27-minute documentary	27 min CST OR 27 min MIST	NASA-TLX: Effort, Frustration, Performance, Temporal demand, Mental demand, Physical demand BRUMS: Fatigue, vigour 5-point motivation scale	BRUMS: ↓ Vigour ($p = 0.018$) ↑ Fatigue ($p = 0.002$) NASA-TLX: ↑ Mental demand ($p < 0.001$), Physical demand ($p < 0.05$), Temporal demand ($p < 0.001$), Performance ($p < 0.01$), Effort ($p < 0.05$) ~ Frustration ($p = 0.329$) Greater scores in MIST for mental and temporal demand compared to CON ($p < 0.001$) and CST ($p < 0.001$); Higher performance subscale scores in CST ($p < 0.01$) and CST ($p < 0.05$) compared to MIST
Salam et al. (2018)	**Trained Cyclists** 11M, Age: 38 ± 6, > 3 years of experience	30-minute of reading a magazine	30 min MIST	10-point scale: MF, Physical fatigue	10-point scale: ↑ MF ($p < 0.01$) ~ Physical fatigue ($p = 0.04$)

Schucker and MacMahon (2016) – study 1 RCT	**Active Individuals** 5M9F, Age: 30.64 ± 13.11, 14.54 ± 8.65 years in sports training	10 min CST	10 min MIST	7-point scale: Cognitive fatigue, Level of effort BRUMS: Fatigue	↑ cognitive fatigue ($p = 0.014$) INT: 3.75 ± 1.14 CON: 2.83 ± 1.11 ↑ Level of effort ($p = 0.043$) INT: 5.08 ± 1.56 CON: 3.17 ± 1.40 ~ BRUMS fatigue
Schucker and MacMahon (2016) – study 2 RCT	**Active Individuals** 5M9F, Age: 30.64 ± 13.11, 14.54 ± 8.65 years in sports training	Watching a 10-minute video	10 min MIST	7-point scale: Cognitive fatigue Level of effort	~ cognitive fatigue ($p = 0.77$) CON: 3.54 ± 1.57; INT: 3.45 ± 1.29 ↑ level of effort ($p = 0.02$) CON: 3.82 ± 2.14; INT: 5.45 ± 1.51
Silva-Cavalcante et al. (2018) Randomised counterbalanced design	**Recreational Road Cyclists** 8M, Age: 33.8 ± 7.2, ~ 5 years of experience	Watching a 90-minute documentary	90 min AX-CPT	100-mm VAS: Fatigue, Motivation	100-mm VAS: ↑ Fatigue ($p = 0.022$) ↓ Motivation ($p = 0.05$)
Smith et al. (2015) Randomised counterbalanced design	**Team Sport Players** 10M, Age: 22 ± 2, > 3 years of competition experience	Watching a 90-minute documentary	90 min AX-CPT	BRUMS: Fatigue, Vigour	BRUMS: ↑ Fatigue ($p = 0.005$) ↓ Vigour ($p < 0.001$)
Slimani et al. (2018) Randomised counterbalanced crossover design	**Active Adolescents** 10M, Age: 16 ± 1.05, high school team sport athletes	30-minute of reading a magazine	30 min MIST (paper version)	BRUMS: Fatigue	BRUMS: ↑ fatigue ($p < 0.001$)
Smith et al. (2016) Randomised crossover design	**Soccer Players** Study 1 12M, Age: 24 ± 0.4, recreational players Study 2 14M, Age: 19.6 ± 3.5, 13.6 ± 3.2 years of experience plus playing in local league game	30-minute of reading a magazine at a comfortable place	30 min MIST (paper version)	Study 1: 100-mm VAS: MF, Mental effort, Motivation Study 2: 100-mm VAS: MF, Mental effort, Motivation	Study 1: 100-mm VAS: ↑ MF ($p < 0.001$) CON: 6 ± 8 vs 12 ± 8; INT:8 ± 9 vs 52 ± 11 ↑ Mental effort ($p < 0.001$) ~ Motivation ($p = 0.423$) Study 2: 100-mm VAS: ↑ MF ($p = 0.016$)

					CON: 35 ± 22 vs 39 ± 25; INT: 22 ± 11 vs 58 ± 22 ↑ Mental effort (p < 0.001) ~ Motivation (p = 0.159)
Smith et al. (2017) Randomised counterbalanced crossover design	**Soccer Players** 14M, Age: 19.6 ± 3.5; 13.6 ± 3.2 years of soccer experience	30-minute reading a magazine	30 min MIST (paper version)	100-mm VAS: MF, Mental effort, Motivation	100-mm VAS: ↑ MF (p = 0.016, d = 0.81), Mental effort (p < 0.001, d = 2.47) ~ Motivation (p = 0.159)
Staiano et al. (2018) Randomised crossover design	**U17 National team kayakers** Age: 16.9 ± 0.8, ~ 5 years of experience in kayaking experience with ~ 5 training per week	Sit comfortably for 60-minute	60 min MIST	NASA-TLX: Effort, Mental demand, Temporal demand BRUMS: Anger, Confusion, Depression, Fatigue, Vigor	NASA-TLX: ↑ Effort, Frustration, Mental demand (ES = 1.89 ± 0.45), Performance, Physical demand (ES = 0.58 ± 0.51), Temporal demand BRUMS: ↑ Anger (ES = 0.86 ± 0.55), Confusion (ES = 0.97 ± 0.44), Depression (ES = 0.85 ± 0.63), Fatigue (ES = 1.01 ± 0.49) ~ Tension ↓ Vigor (ES = -0.89 ± 0.65)
Trecroci et al. (2020) Randomised counterbalanced crossover design	**Soccer Players** 9M, Age: 17.6 ± 0.5; ≥ 4 training sessions per week	Watching a 30-minute documentary	30 min IST on smartphone	Borg's CR10: RPE 100-mm VAS: MF, Mental effort, Motivation	Borg's CR-10: ~ RPE (p = 0.424) 100-mm VAS: ↑ MF (ES = 1.88, p = 0.001), Mental effort (p < 0.001) ~ Motivation (p = 0.82)
Van Cutsem et al. (2019) Randomised crossover design	**Healthy** 5M6F, Age: 25 ± 4; not engaged in any kind of regular physical activity for last 5 years **Badminton player** 5M4F, Age: 23 ± 3; ≥8 years badminton experience	Watching a 90-minute documentary	90 min MIST	100-mm VAS: MF NASA-TLX: Effort, Mental demand, Temporal demand	100-mm VAS: ↑ MF (p = 0.029) NASA-TLX: ↑ Effort, Mental demand, Temporal demand, Physical demand, frustration (p ≤ 0.011) ~ Performance
Veness et al. (2017) Randomised crossover design	**Cricket Players** 10M, Age: 21± 8; ≥ 2 years of experience in a professional club	30-minute of reading a magazine	30 min IST	100-mm VAS: MF, Motivation	100-mm VAS: ↑ MF (p < 0.001) CON: 13.5 ± 2.7 vs 16.6 ± 3.6; INT: 14.4 ± 2.1 vs 46.6 ± 5.9 ~ Motivation (p = 1.00)

Verschueren et al. (2020) Randomised counterbalanced crossover design	**Recreational Active** 10M4F, Age: 22 ± 1, > 3 years of competition experience	Watching a 90-minute documentary	90-minute IST	100-mm VAS: MF NASA-TLX: Effort, Mental demand, Temporal demand, Frustration, Physical demand, Performance Perception of task success Intrinsic motivation	100-mm VAS: ↑ MF (p = 0.002) CON: 31.92 ± 5.67 vs 35.69 ± 6.1; INT: 28.77 ± 5.7 vs 62.92 ± 5.49 NASA-TLX: ↑ Effort (p = 0.007), Mental demand (p < 0.001), Temporal demand (p = 0.012), Frustration (p = 0.001) ~ Performance, Physical demand ~ perception of task success ~ intrinsic motivation
Vrijkotte et al. (2018) Randomised placebo-controlled crossover design	**Cyclists** 9M, Age: 26 ± 6	90-minute rest	90 min IST	100-mm VAS: MF POMS: Tension, Depression, Anger, Fatigue, Vigour	100-mm VAS: ↑ MF (p = 0.02, d = 0.49) POMS ↑ Fatigue (p < 0.01, d = -2.05), Tension (p < 0.01) ~ Depression (p = 0.14), Anger (p > 0.05), Vigour (p = 0.11)
Vogt et al. (2018) RCT	**Soccer Players** 33M, Age: 13.5 ± 1.0; 10.0 ± 1.4 years of experience in soccer competing at the highest regional or national youth level	20 min watching football highlights, reading a magazine or talking to other participants	10 min IST and 10 min determination test	100-mm VAS: MF	100-mm VAS: ↑ MF (p < 0.001)
Zering et al. (2017) Randomised counterbalanced design	**Untrained and Recreational active university students** 7M8F, Age: 19.56 ± 1.69	Watching a 10.5-minute documentary	10.5 min Stop-signal task	Borg's 10-point scale: Mental exertion	Borg's 10-point scale: ↑ Mental exertion (p < 0.001) CON: 1.29 ± 1.36; INT: 4.37 ± 1.92

↑: increased significantly; ↓: reduced significantly; ~ : similar to no significant difference compared to CON; AX-CPT: AX Continuous Performance Test; BRUMS: The Brunel Mood Scale; F: Female; IST: Incongruent Stroop Task; M: Male; MF: Mental Fatigue; MIST: Modified Incongruent Stroop Task; VAS: 100-mm Visual Analogue Scale; NASA-TLX: NASA Task Load Index; POMS: The Profile of Mood States IST: Incongruent Stroop Task.

2.5.2.1 Profile of Mood States (POMS)

The Profile of Mood States (POMS) is a 65-item questionnaire that comprises six different mood dimensions: anger, confusion, depression, fatigue, tension and vigour (Terry et al., 2003). The presence of MF is known to have a negative impact on mood (Van Cutsem et al., 2017). According to Table 2.6, only five studies have employed POMS to examine fatigue and other mood changes following an MF protocol (Boat & Taylor, 2017a; MacMahon et al., 2014; Martin et al., 2015; Pires et al., 2018; Vrijkotte et al., 2018). However, the selection and utilization of POMS subscales to subjectively measure mood states and MF varied among studies, requiring cautious interpretation of the results. Specifically, two studies employed the fatigue subscale of POMS as the primary subjective measurement for assessing MF (Boat et al., 2017a; MacMahon et al., 2014). The remaining three studies incorporated both fatigue and vigour subscales of POMS (Martin et al. 2015), a 24-item POMS with six different subcategories: tension, depression, anger, vigour, fatigue and mental confusion (Pires et al., 2018) or a 32-item POMS without the mental confusion subcategory (Vrijkotte et al., 2018). The different administrations of POMS suggest that there is no standardisation in the total number of included categories or assessed items in MF research (MacMahon et al., 2014; Martin et al., 2015; Pires et al., 2018; Vrijkotte et al., 2018). The lack of consistency limits the comparability and replicability of the research, increasing the challenges associated with reaching an accurate conclusion on whether POMS is an effective measurement for MF. Moreover, the unstandardised usage of POMS subscales may result in conceptual confusion and inconsistent understanding of MF.

The POMS fatigue subscale ratings increased significantly following the MF protocol ($p < 0.05$) (MacMahon et al., 2014; Vrijkotte et al., 2018), with an extremely large increase ($d = -2.05$) observed in Vrijkotte et al. (2018). However, this was not consistently observed, as other studies reported insignificant changes in mentally fatigued individuals (Boat et al., 2017a; Martin et al., 2015; Pires et al., 2018). The discrepancy between studies could be attributed to the inconsistent utilization of the POMS. It remains unclear whether the extremely large increase in Vrijkotte et al. (2018) is related to the number of subscales included, as Pires et al. (2018) utilised six POMS subscales but found no significant increase in the fatigue subscale. Another potential explanation is that Boat et al. (2017a) only utilised two items from the fatigue subscale (Boat et al., 2017a), in contrast to other studies that included all four items from the

POMS fatigue subscale (MacMahon et al., 2014; Vrijkotte et al., 2018; Martin et al., 2015; Pires et al., 2018). Furthermore, the two items of the POMS fatigue subscale in Boat and Taylor (2017a) were specifically designed to measure physical fatigue, which may explain the differences between studies. It is essential to reinforce that MF is different from other fatigue constructs. The potential mechanism of MF is related to the time spent on cognitively demanding tasks (Van Cutsem et al., 2017), and previous research has shown its distinction from other fatigue-related variables such as stress, tiredness, and physical fatigue (Russell et al., 2022). The differences in the results of the studies discussed above could be attributable to the fact that the fatigue subscale of the POMS was not primarily designed to measure MF, and hence lacked sensitivity in measuring MF.

In addition to the rating of fatigue subscales, the changes in the vigour subscale of the POMS following an MF protocol demonstrated conflicting results. Only Pires et al. (2018) reported a significant decrease in vigour, while no significant difference was identified in Martin et al. (2015) and Vrijkotte et al. (2018). The conflicting results observed in vigour and fatigue ratings following MF protocols might be related to variations in the standardisation of the pre-experiment condition. Similar restrictions on vigorous exercise and caffeine consumption have been reported in other research (MacMahon et al., 2014; Pires et al., 2018; Boat et al., 2017a; Vrijkotte et al., 2018).

In addition to these restrictions, Martin et al. (2015) was the only study that required participants to sleep for at least seven hours the night before the experiment. This pre-experiment standardisation addressed a potential confounding variable, as previous research has indicated that insufficient sleep may lower the psychological threshold and increase negative mood the following day when encountering cognitively stressful tasks (Minkel et al., 2012). It should also be noted Martin et al. (2015) is the only study that permitted water consumption throughout the experiment, implying participants had the opportunity to distract their attention during the MF protocol, whereas participants in other studies were fully concentrated on performing the task.

Furthermore, the BRUMS vigour subscale measures individuals' perceptions of alertness and excitement (Terry et al., 2003). A reduction in vigour scores could imply both boredom and MF, while MF is often caused by continuous cognitive exertion on mentally demanding tasks (Van Cutsem et al., 2017). This does not entirely rule out the potential link between boredom and MF because boredom is associated with decreased engagement and interest in activities, which can manifest similarly to MF. Increased MF levels may result in decreased vigour because sustaining a high level of concentration and effort over an extended period can be mentally demanding. It has been observed the negative mood states of the POMS are higher in the morning, whereas the positive mood states are higher in the evening (Essid et al., 2022). Except for Boat et al. (2017a), all studies discussed in this section specify the experiments and measurements were conducted at the same time of day (Pires et al., 2018; MacMahon et al., 2014; Martin et al., 2015; Vrijkotte et al., 2018). However, only Vrijkotte et al. (2018) explicitly specified that the experiments were conducted in the morning. As a result, it is unclear if the ratings in the other studies were already influenced by the time of day before the start of the experiment.

Furthermore, as MF is characterised as a psychobiological state (Van Cutsem et al., 2017), it is important to acknowledge that the changes in perceived MF can evoke negative psychological responses, which may differ between individuals because MF is subjective. Assessing mood, such as vigour, may not directly signify the presence of MF, but it can help justify the effects of MF. This is because there are similarities between perceived MF and reduced interest and engagement in tasks as mentioned above. However, depending primarily on the POMS may result in a lack of sensitivity in measuring MF. Most research has predominantly focused on the use of vigour and fatigue subscales without justifying the inclusion or exclusion of other subscales, and this lack of clarity limits the use of POMS in MF research. Additionally, Russell et al. (2022) reported significant differences between self-reported MF ratings, mood, stress, and motivation ratings across two elite netball seasons. This evidence suggests that the POMS, which was originally designed to measure individuals' mood states, may not be directly suitable for measuring MF.

2.5.2.2 Brunel Mood Scale (BRUMS)

The BRUMS, a simplified version of the POMS, has a high internal consistency ($\alpha = 0.85$) (Brandt et al., 2016). It is more commonly used in MF research than the POMS for measuring mood states, as it was specifically designed for application in sporting contexts (Lan et al., 2012; Rohlfs et al., 2008). The BRUMS is a 24-item questionnaire that assesses anger, confusion, fatigue, depression, tension, and vigour (Brandt et al., 2016; Lan et al., 2012).

Previous research has shown that the BRUMS is more efficient than the POMS, as it significantly reduces the number of items required to measure athletes' mood states (Brandt et al., 2016; Lan et al., 2012). Similar to the POMS, only the vigour and fatigue subscales of the BRUMS were frequently employed, as shown in Table 2.6 (Filipas et al., 2019; Filipas et al., 2018; Holgado et al., 2020; Lam et al., 2021; Lopes et al., 2020; Marcora et al., 2009; Pageaux et al., 2014; Pageaux et al., 2015; Roussey et al., 2018; Rozand et al., 2014; Slimani et al., 2015; Smith et al., 2015). One study focused exclusively on the fatigue subscale of the BRUMS (Schücker & Macmahon, 2016), whereas another study employed all six BRUMS subscales (Staiano et al., 2018). The inclusion of all six subscales in the BRUMS could be due to the aim of assessing both positive and negative mood states in individuals, rather than just measuring MF.

Out of the thirteen included studies, ten reported significant increases ($p < 0.05$) in the BRUMS fatigue subscale following an MF protocol (Filipas et al., 2019; Holgado et al., 2020; Lam et al., 2021; Lopes et al., 2020; Marcora et al., 2009; Pageaux et al., 2014; Rozand et al., 2014; Smith et al., 2015; Staiano et al., 2018; Slimani et al., 2018), and eight out of twelve included studies demonstrated significant decreases ($p < 0.05$) in the vigour subscale (Smith et al., 2015; Pageaux et al., 2014; Marcora et al., 2009; Filipas et al., 2019; Holgado et al., 2020; Lam et al., 2021; Staiano et al., 2018; Rozand et al., 2014). These findings indicate the sensitivity of the BRUMS in detecting mood changes associated with MF. However, the specificity of these changes to MF is questionable, given that the subscale items were not specifically designed for MF measurement. Most studies employed the BRUMS as a secondary indicator of MF, with only two studies using the BRUMS vigour and fatigue subscales as primary MF measures (Smith et al., 2015; Marcora et al., 2009). However, as discussed in section 2.5.2.1, these two subscales assess the multifaceted mood dimension rather than MF-specific symptoms, raising questions about the suitability of these scales as primary measures of MF. A mini meta-analysis of five laboratory-based experiments found no significant impact of MF ($p = 0.996$) on BRUMS vigour scores (Slimani et al., 2017). Furthermore, Slimani and Bragazzi (2017) discovered no significant difference regarding the impact of MF on vigour scores between trained or physically active individuals ($p = 0.843$), suggesting that BRUMS vigour changes were not sensitive to detecting MF in either population. Therefore, future work should use the BRUMS solely for mood assessment and not as a primary indicator of MF.

The BRUMS and POMS shared a similar limitation: the items in the BRUMS fatigue subscales, such as worn out, exhausted, sleepy and tired (Brandt et al., 2016), do not align with the definition of MF (Van Cutsem et al., 2017). Using BRUMS fatigue subscales as a primary indicator of MF might lead to response bias, as it does not accurately reflect the symptoms of MF and could be confused with another type of fatigue. The rationale for excluding other BRUMS subscales in MF research is unclear, similar to the POMS. Given the complexity and subjective interpretation of MF, the effects of MF may vary among individuals (Thompson et al., 2020). It is recommended that the BRUMS be used exclusively for assessing mood states (Lan et al., 2012; Brandt et al., 2016), rather than measuring MF.

2.5.2.3 National Aeronautics and Space Administration Task Load Index (NASA-TLX)

The NASA-TLX scale measures subjective mental workload and situation awareness using six subscales (Braarud, 2020; Huggins & Claudio, 2018; Said et al., 2020). The NASA-TLX scale is similar to the VAS but categorises specific areas in each subscale. According to Table 2.6, eighteen studies implemented the NASA-TLX, with four studies employing a modified version (Filipas et al., 2020; Martin et al., 2016; Martin et al., 2019; Staiano et al., 2018). Three studies excluded the performance subscale (Filipas et al., 2020; Martin et al., 2016; Martin et al., 2019), while the remaining studies excluded the temporal demand (Martin et al., 2019), frustration (Rozand et al., 2014), and physical performance subscales (Martin et al., 2016). However, the exclusion of these subscales was not justified (Filipas et al., 2020; Martin et al., 2016; Martin et al., 2019; Rozand et al., 2014). The selective use of NASA-TLX subscales can result in inconsistent interpretations of findings, as each subscale represents a different perceived workload. While justifying the exclusion of specific NASA-TLX subscales is essential, it is also important to acknowledge that NASA-TLX was primarily developed to assess mental demand and perceived workload, and it was not designed for measuring MF. The inclusion of NASA-TLX in MF research is meant to evaluate the effectiveness of MF interventions, as MF is defined as a result of prolonged engagement in mentally demanding tasks (Van Cutsem et al., 2017). Including NASA-TLX can reflect the perceived mental workload during MF interventions and provide insights into the effectiveness of challenging mental demands. However, it is important to recognise that NASA-TLX does not directly measure perceived MF.

Table 2.6 shows that mentally fatigued individuals often report a significant increase in the ratings of mental demand, temporal demand, effort, and frustration in NASA-TLX. However, the effects of MF on the physical demand and performance subscale presented inconsistent results. These inconsistent changes may be attributed to the fact that the MF protocol focused on challenging the cognitive demand, possibly not affecting these subscales significantly. Therefore, future MF research might consider excluding frustration, physical demand, and performance subscales. Furthermore, previous research has shown that the NASA-TLX remains a valid and reliable measurement tool for measuring subjective workload, even with slight modifications to the subscale content (Galy et al., 2018; Hoonakker et al., 2011; Said et al., 2020; Wilson et al., 2011).

The NASA-TLX was specifically designed to assess mental workload and demand, not to measure MF. Therefore, if the investigation aims to examine changes in perceived MF, the NASA-TLX might be inappropriate for measuring the MF levels of individuals. This suggests that while the NASA-TLX can effectively measure mental workload, it should not be utilised as a primary measure for MF.

2.5.2.4 100-mm Visual Analogue Scale (VAS)

The Visual Analogue Scale (VAS) is a frequently used and reliable measurement tool in clinical and research settings for assessing subjective experiences, such as fatigue ($\alpha = 0.95$) (Lee et al., 1991; McCormack et al., 1988). Table 2.6 shows that the 100-mm VAS is routinely employed to measure MF. However, there were inconsistencies in the anchors used for VAS MF measurement in the discussed evidence in Table 2.6. The inconsistency might be attributed to the design of the VAS. The evidence summarised in Table 2.6 shows that the VAS for MF involves responding to questions such as “How mentally fatigued do you feel now?” (Fortes et al., 2020; Vrijkotte et al., 2018; Fortes et al., 2021; Fortes et al., 2021; Fortes et al., 2021) or “What is your mental fatigue level now?” (Holgado et al., 2020). Most studies in Table 2.6 did not clearly define MF for participants before the experiments. The lack of a clear MF definition may lead to participant responses based on their interpretation and understanding of MF.

Additionally, previous research has found that athletes and practitioners may have different interpretations and conceptualizations of MF (Russell et al., 2019). To ensure consistency and minimise potential differences in MF conceptualisation among participants, future research should standardise and provide an evidence-based definition of MF, as well as include appropriate VAS anchors to enhance the accuracy and comparability of MF assessments across different studies. While MF is defined as a subjective feeling that occurs following a cognitively demanding task (Van Cutsem et al., 2017; Habay et al., 2021), it is important to acknowledge that individual differences in interpreting and experiencing MF are inevitable due to its subjective nature. The lack of standardisation in VAS anchors could compromise the internal validity of study findings and decrease data comparability between studies.

Despite the lack of standardised terminology for measuring MF using the VAS, most studies in Table 2.6 reported a significant increase in perceived MF through VAS, except for Brown et al. (2021). However, Brown et al. (2021) measured MF at two-minute intervals during a 10-minute MF protocol, revealing a significant increase over time within the condition ($p < 0.001$), but not in comparison to a control condition. This reflects that the VAS effectively captures MF changes over time. In addition to individual differences in the perception of MF discussed above (Russell et al., 2019), an investigation involving 256 youth English academy soccer players found that common descriptions of MF included motivation, concentration, and reaction to mistakes (Thompson et al., 2020). There is a risk of participants interpreting MF as other fatigue-related variables, such as physical fatigue, tiredness, or stress, especially since tiredness is also proposed to be associated with MF (Habay et al., 2021; Van Cutsem et al., 2017; Martin et al., 2018). This highlights the potential interpretation issues due to the varying terminologies used in the VAS. Considering the absence of an ideal subjective measurement tool for MF, the 100-mm VAS remains the most appropriate subjective measure for MF (Smith et al., 2019). Improving participants' understanding of MF, as discussed in section 2.4.3, may potentially reduce response bias in the VAS, as suggested by Thompson et al. (2019). Lastly, it is recommended to advance the application of the VAS in MF measurement by encouraging consistent anchors and standardising the terminology 'mental fatigue' to improve clarity.

The VAS has demonstrated high reliability in paired measurements of perceived pain, with an intraclass correlation coefficient (ICC) of 0.97, and 90% of the ratings were reproducible within a 9 mm range when measured every 30 minutes over a two-hour period (Bijur et al., 2001). Similar results were observed when comparing the retest reliability between the VAS and numeric scales, with an ICC of 0.97 and a standard error of 0.03 (Alghadir et al., 2018). However, a systematic review reported that the median absolute minimum clinically important difference in studies with high variability in ratings could be as high as 20 mm (Olsen et al., 2018). It is important to note that these findings were primarily related to pain assessment rather than MF, and the population studied typically involved patients with varying levels of pain. This does not negate the effectiveness of using the VAS to assess MF, as its utility should be content-specific. While these findings indicate that the VAS is a reliable tool for assessing subjective responses, further investigation is needed to determine the typical variability in perceived MF. To the best of the author's knowledge, there is currently no conclusive evidence on how much change in VAS ratings represents a definite change in perceived MF, nor any studies specifically examining the test-retest reliability of VAS for MF. Nevertheless, the VAS remains the recommended tool for measuring perceived MF (Smith et al., 2019).

2.5.2.5 Likert and Numeric Scale

Seven studies in Table 2.6 employed numeric scales to measure perceived MF. However, there is a discrepancy in the maximum number on these scales: two studies utilised a 7-point scale (MacMahon et al., 2019; Schucker & MacMahon, 2016), while four studies used a 10-point scale (Salam et al., 2018; Boat and Taylor, 2017a; Boat et al., 2021a; Graham et al., 2017; Zering et al., 2017). This inconsistency in scale selection complicates the interpretation of results. Importantly, three studies in Table 2.6 specifically measured MF using a numeric scale (MacMahon et al., 2019; Salam et al., 2018; Schucker & MacMahon, 2016), whereas the remaining studies measured mental exertion (Boat and Taylor, 2017a; Boat et al., 2021a; Graham et al., 2017; Zering et al., 2017). This variation highlights a lack of specificity and consistency in the subjective measurements employed. Consequently, this variability compromises the reliability of the numeric scale as a subjective measure for MF, demonstrating that it is less dependable than the VAS for assessing perceived MF.

2.5.2.5.1 The Rating-of-Fatigue Scale (ROF)

Previous research has developed an 11-point Likert scale to measure perceived fatigue, which is considered more accurate than other subjective measurement tools for assessing perceived fatigue (Micklewright et al., 2017). This is attributed to its inclusion of five descriptors and five diagrams that assist individuals in understanding the ratings on the scale (Micklewright et al., 2017). Although the ROF scale has been reported to have high validity in measuring perceived fatigue (Micklewright et al., 2017), this validity is primarily based on ramped cycling to exhaustion. Moreover, the ROF scale shares similar limitations with other subjective measures discussed in sections 2.5.2.1 to 2.5.2.3, as it does not directly measure MF. Despite Micklewright et al. (2017) highlighting the potential differences between perceived exertion and perceived fatigue using the ROF scale, the anchor used in the ROF scale refers to general fatigue rather than MF, similar to the unstandardised anchors reported in section 2.5.2.4.

Furthermore, similar challenges in interpreting clinically meaningful changes, as discussed in section 2.5.2.4, have been identified when using Likert and numeric scales. Previous research suggests that for scales ranging from 0 to 10, a minimum change of 2.5 points is recommended to indicate clinically significant improvement (Pool et al., 2007). Any changes below this threshold may be considered within the margin of error and may not accurately represent a true change in the ratings. However, as highlighted in section 2.1.4, it is essential to recognise that perceived MF is entirely subjective, and even increases below 2.5 points could still affect physical performance (Boat et al., 2021a; Boat et al., 2017).Additionally, the minimal important change and smallest detectable change can vary depending on the population (Schuller et al., 2014), indicating that applying a universal threshold to define clinically meaningful change may be inappropriate. As concluded in section 2.5.2.4, findings from subjective measures should therefore be interpreted with caution. Furthermore, the limited application of the Likert scale in MF research, as shown in Table 2.6, suggests potential limitations in its specificity and acceptance. This may further question its suitability, particularly given the limited understanding of MF. Consequently, this weakens the rationale for using the ROF scale or similar Likert scales to measure perceived MF.

2.5.2.6 Limitations of the subjective measurements of mental fatigue assessment

To accurately measure MF subjectively, the scale employed should precisely capture the nature of MF without confusing it with other related variables such as stress, mental workload or mental demand. However, a major limitation identified in sections 2.5.2.1 to 2.5.2.4 is the lack of a clear MF definition and an understanding of MF among participants. This vagueness may affect the precision of the measurements, as individuals may have different interpretations of MF (Russell et al., 2019). Importantly, previous research conducted with elite netballers over two seasons showed significant differences between MF changes and other fatigue-related variables, such as tiredness, physical fatigue, and stress experienced by the athletes (Russell et al., 2022). This highlights the limitations of using low-specificity subjective measures for MF, potentially leading to errors in accurately identifying and evaluating MF. However, developing more precise subjective measures of MF is challenging without a thorough understanding of the phenomenon, risking the creation of tools that are inadequate to capture the complexities of MF. To enhance measurement precision, it is crucial to initially explore athletes' understanding and interpretation of MF. Given that individuals may perceive MF differently, establishing a standardised baseline of understanding of MF among athletes through empirical investigation is essential. Despite the limitations of subjective measures, they remain the most suitable measurement for assessing MF due to their subjective nature.

There is a limitation in relying on a single subjective measure of MF to validate its presence. The NASA-TLX primarily focuses on assessing task-related mental workload, which may be relevant to MF. However, as discussed in section 2.5.2.3, the NASA-TLX can only reflect the perceived workload associated with a task, rather than directly indicating the level of MF. Therefore, relying on NASA-TLX may only lead to an incomplete representation of MF. A similar limitation exists in the ROF scale as mentioned in 2.5.2.5 as it was not primarily designed to measure MF but general fatigue during and after exercise. As such, using ROF as a subjective measurement tool for MF might be inappropriate. Moreover, the BRUMS and POMS are frequently utilised in MF research, but often only the vigour and fatigue subscales of the BRUMS and POMS are used. While it is true that MF can impact an individual’s mood state (Van Cutsem et al., 2017), relying solely on mood state measurements may overlook the true effects of MF, as other factors like boredom and stress could also contribute to changes in mood state. Compared to the previously mentioned subjective measures, the VAS is most frequently used in MF research, as it allows individuals to freely indicate their MF level on a scale between the minimum and maximum levels of MF. However, the VAS is susceptible to bias due to the potential individual differences in interpreting MF (Thompson et al., 2019). Without a clear definition of MF, it is debatable whether the significant changes observed in subjective measurements are primarily attributable to MF.

Additionally, as shown in Table 2.6 and discussed in sections 2.5.2.4 and 2.5.2.5, perceived MF was measured using either the VAS or a 0-10 Likert or numeric scale. However, both subjective measurement tools face similar limitations in interpreting meaningful changes in ratings. It is important to recognise that this issue is not unique to MF research but also applies to studies measuring subjective psychological responses (Schuller et al., 2014; Pool et al., 2007; Olsen et al., 2014). Therefore, while the findings presented in Table 2.6 using these subjective tools should not be entirely disregarded, more caution is warranted when interpreting the results.

Despite the limitations of the VAS in subjectively measuring MF, the VAS employed in previous research, as mentioned in section 2.5.2.4, was specifically designed for measuring MF. It could be beneficial to include other measurement tools as supplementary subjective measures to provide additional information that may enhance the identification of MF. The use of these supplementary scales can facilitate a more precise examination of MF-related effects.

2.5.2.7 Recommendations

In conclusion, while computerised MF protocols have offered valuable insights into the effects of MF on sports performance, this thesis suggests the necessity for a more sport-specific and holistic understanding of mental fatigue in the athletic context. Future research should aim to comprehend the complex and multifaceted nature of MF as experienced by athletes in real sporting environments. It is believed this thesis contributes to advancing knowledge of the effects of MF on athletic performance and ultimately contribute to the development of targeted strategies to optimise both athlete well-being and performance. The discussion in sections 2.5.2.1 to 2.5.2.5 highlights the importance of standardising the terminology and establishing a clear fundamental understanding of MF among participants before the experiments. Such standardisation is crucial for improving the internal validity of research and ensuring comparability across studies using subjective measurements. Moreover, it is recommended that future research employ measurement tools specifically designed for measuring perceived MF to minimise misinterpretation of the results and avoid inaccurate conclusions on the effects of MF. For example, the VAS should be employed to assess perceived MF, while the BRUMS and NASA-TLX are recommended for measuring mood state and mental workload, respectively.

Although interpretating meaningful changes in the VAS may be more challenging compared to Likert scale and numeric, it is important to acknowledge that Likert and numeric scale may provoke confusion and increase respondent burden. Previous research has highlighted that multiple-item measures could be more cogntiively demanding and could potentially affect psychological responses (Allen et al., 2022; Fisher et al., 2016). This is particularly concerning in research measuring psychological responsese, espeically when our understanding of MF is limited as presented in section 2.1.4 and 2.3. Such limitations may increase respondent bias as respondents may feel the need to respond differently when multiple psychological variables are assessed simultaneously (Fisher et al., 2016). This may also explain why the majoritiy of the research in Table 2.6 utilised the VAS to measure perceived MF instead of Likert scale as shown in 2.5.2.5. While Likert scales are valued for their structured approach, the VAS offers distinct advantages in capturing subtle variations in subjective experiences. This is especially relevant in this thesis, as using a tool that reduces cognitive load and simplifies the response process ensures both the validity and reliability of the data, aligning with best practices for repeated measures experiments. To conclude, future research should priotise the use of the VAS for measuring MF while providing a clear rationale for the inclusion of specific subjective measures. Excluding certain subscales without a detailed explanation could compromise the validity and reliability of the findings.

2.5.3 Overall summary of the mental fatigue literature

Based on the literature review presented in this thesis, it is evident that MF is a phenomenon that occurs following engagement in cognitively demanding tasks. This leads to impairments in endurance performance, subjective feelings of MF, mood state, and the speed and accuracy of decision-making, but does not significantly affect anaerobic performance. However, the underlying mechanisms and nature of MF remain insufficiently understood. An increase in the perception of MF may be detrimental to endurance performance and cognitive performance, as reflected in RT and decision-making accuracy. Due to the insufficient understanding and complex nature of MF, identifying the ideal subjective and objective measures for MF assessment is challenging. Consequently, researchers often rely on widely used measurement tools in the literature, such as the VAS, to measure MF, which can enhance the comparability of results and align with the subjective nature of MF.

Besides, there is inconsistency in the scales and tools employed for both subjective and objective MF measurements. The inconsistency complicates the synthesis of results across studies. Despite the inconsistent use of measurement tools, previous research has reported that changes in perceived MF differ from changes in other fatigue-related variables such as physical fatigue, stress, mood, and tiredness (Abbott et al., 2020; Russell et al., 2022). Another challenge observed in the literature is the ecological validity of laboratory-based research. Most research heavily relies on computerised cognitively demanding tasks to investigate MF. While these tasks have been shown to increase perceived MF upon completion, they do not fully reflect real-world scenarios, especially in sports where physical and cognitive efforts are involved. Additionally, the MF protocols are conducted in well-controlled laboratory environments with little to no distractions, which may limit the relevance of the findings to sporting populations.

In short, this thesis highlights the importance of ongoing investigation into the underlying mechanism of MF, as well as the development of standardised and consistent methodologies for measuring MF. This thesis recognises the uniqueness of MF, which should be distinguished from other fatigue-related constructs. Importantly, this thesis suggests shifting the focus of future research away from laboratory-based experiments. Instead of attempting to experimentally induce MF, this thesis suggests exploring whether MF occurs naturally in sports. This includes examining the perspective of athletes and coaches on MF to improve the understanding of MF in real-world sports contexts. It is believed not only does this approach address the limitations regarding the ecological validity of laboratory-based MF protocol, but it could also bridge the gap to practical application.

2.6 Physical and Perceptual-cognitive Demands of Orienteering

2.6.1 Introduction

Orienteering is an endurance cross-country running sport that combines physical and perceptual-cognitive skills. Orienteers must manage both physiological and psychological demands to interpret the map and attend each control point accurately using a compass (Celestino et al., 2015; Creagh & Reilly, 1997). The completion time for orienteering races varies, with short-distance races taking approximately 30 minutes and classic-distance races lasting approximately 90 minutes (Creagh & Reilly, 1997). Moreover, orienteering is described as an individualised forest terrain running TT, as orienteers start at different times with an individualised running route (Creagh & Reilly, 1997). According to the International Orienteering Federation, there are five different types of orienteering competitions, including knockout sprint, relay, sprint, middle- and long-distance, with the distance ranging from 1km to 16km. This racing format makes the race entirely self-paced, emphasising the importance of conscious decision-making and the ability to balance physical output in orienteering. The physiological demands and completion time of orienteering vary depending on the chosen running route and any potential mistakes made by the orienteers. This establishes that orienteering races vary in distance and duration, requiring both anaerobic and aerobic energy output, as well as varying degrees of cognitive effort from orienteers. The following section will further explore the physical and cognitive demands of orienteering and provide a rationale for investigating MF in this sport.

2.6.2 Physiological Demands in Orienteering

2.6.2.1 Heart Rate

Previous systematic reviews have reported the average HR of orienteers during races ranges between 150 and 200 beats per minute (BPM), which is comparable to the mean HR of marathon runners, at 171 BPM (Batista et al., 2020; Creagh & Reilly, 1997). Previous research comparing the performance of ten elite orienteers between treadmill tests and field tests reported that the large variance in HR could be attributed to the different types of terrain encountered in orienteering (Larsson et al., 2002). Additionally, this discrepancy reflects environmental conditions, the training status of individuals, and the duration of the race, all of which could contribute to the large variance, as orienteers are required to identify the most appropriate route based on their abilities, leading to differences between orienteers. However, most studies in the previous systematic review did not specify the type of orienteering race, making it difficult to determine HR differences between various race types (Batista et al., 2020; Creagh & Reilly, 1997). Furthermore, some data were obtained from simulated orienteering races rather than actual competitions, which could lead to variations in the average HR for orienteering races compared to the range mentioned in the review.

The peak HR value of elite orienteers during orienteering can reach up to 90% of their maximum HR, reflecting the substantial involvement of aerobic output (Batista et al., 2020). This is consistent with earlier research demonstrating that the mean HR of a trained orienteer can reach close to their maximum HR regardless of the orienteer's age (Bird et al., 2003a; Bird et al., 2003b; Jensen et al., 1999). The high HR reflected the substantial physical effort involved in orienteering. Moreover, the mean HR tends to be lower when orienteers encounter technically challenging terrain that requires slower running for navigational accuracy, (Bird et al., 1993). Conversely, a higher mean HR may result from physically challenging terrain or easier terrain that allows for high-speed running (Bird et al., 1993). However, it is crucial to interpret these results with caution due to the wide age range of the participants, ranging from 15 to 62. The age, training and maturation status of the participants can directly affect the accuracy of the findings. In summary, these findings emphasise that orienteers experience significant physiological stress and run at relatively high intensity during orienteering competitions. These findings suggest that variation in HR depends on the complexity of the terrain.

2.6.2.2 VO2max

The maximal oxygen uptake (VO_2max) of elite male orienteers has been found to range from 57.2 to 79 ml $kg^{-1}min^{-1}$ (Batista et al., 2020; Jensen et al., 1999; Smekal et al., 2003). A comparison of VO_2max between Danish national level orienteers and track runners showed a similar value, 73 ml $kg^{-1}min^{-1}$ and 74 ± 4 ml $kg^{-1}min^{-1}$, respectively. This supports the findings of an earlier systematic review, which suggested that the physiological stress on the aerobic system in orienteering is akin to that of marathon running (Creagh & Reilly, 1997). As discussed in section 2.6.2.1, although previous research did not specify the type of orienteering races conducted, the elevated mean HR observed in orienteers during orienteering races highlights the demand for high energy output, particularly in terms of aerobic capacity. The specific energy demand of orienteering may vary depending on the technical difficulty of the course, which includes negotiating obstacles, steep hills and surface vegetation encountered during the race (Larsson et al., 2002), underlining the unclear contribution of aerobic and anaerobic output during orienteering.

While the training status influences the running economy of orienteers on different horizontal paths and terrain (Jensen et al., 1994; Jensen et al., 1999), it does not alter the fact that orienteering is a sport that requires high aerobic demand. Previous systematic reviews have shown that sub-elite and elite orienteers could reach 79-91% of their peak VO_2max during a simulated orienteering competition (Batista et al., 2020), further reinforcing the need for high aerobic capacity in orienteering. However, there is minimal information available about the VO_2max of female orienteers. These findings do not specify which type of races the orienteers specialised in or participated in, as the physiological output required for these different types of races may differ. To summarise, the lack of individual characteristics makes it impossible to compare the differences between orienteers of different specialities in the sport. However, it remains reasonable to summarise that aerobic capacity plays an important role in orienteering.

2.6.2.3 Blood lactate level

A recent systematic review reported that the BLa levels of orienteers before and after a simulated orienteering competition ranged from 3 to 11 mmol/L (Batista et al., 2020). More specifically, Creagh & Reilly (1997) found that elite male orienteers had a mean BLa level of between 3.6 and 4.6 mmol/L during high technical demands races and a higher level of 4.4 to 6.7 mmol/L during less complex races. This implied that orienteering requires both aerobic and anaerobic capacity, and should be considered an intermittent endurance sport. The variation in BLa levels during the race may be attributed to the complexity of the terrain, where orienteers may intentionally slow down or stop to navigate to the next checkpoint (Creagh & Reilly, 1997; Smekal et al., 2003). However, running uphill and downhill, poor vision in the forest, and other difficult portions of the course may also contribute to fluctuations in BLa levels. It is important to acknowledge that the stop-start nature of orienteering could also contribute to the fluctuation in BLa levels. The broad range of BLa levels observed among orienteers may be attributed to their ability to choose routes based on their physical capabilities. Well-trained orienteers can effectively maintain their focus on relevant visual and environmental information, executing their tactical plans without the need to stop during the race (Batista et al., 2020). Therefore, this variation in BLa levels can be primarily associated with their decision-making rather than the physical demands of the task.

As mentioned above, orienteers can design their unique running route during orienteering races, it is possible that orienteers intentionally reduce high-intensity activity during orienteering competition to avoid physical stress, as this could affect their accuracy of navigation and increase the chances of making mistakes (Batista et al., 2020; Smekal et al., 2003). The low BLa levels found among some orienteers may simply indicate they have chosen an optimal route that is less physically demanding than others, which could explain the differences in BLa levels within the same orienteering race. Since the interpretation of technical difficulty may vary depending on the individual and the feasibility of measuring BLa during orienteering is low, the BLa level of the orienteers may be less important in differentiating levels of orienteers. Therefore, when measuring the BLa during orienteering races, it is important to consider various factors such as race duration, training status, terrain complexity, and the timing of BLA measurements. It may be sensible to measure BLa alongside other physiological parameters such as HR to accurately evaluate the performance of the orienteers.

2.6.3 Cognitive and psychological demands in orienteering

2.6.3.1 Multitasking in Orienteering

The fundamental nature of orienteering requires orienteers to manage their cognitive and physical output, highlighting the importance of multitasking. An interview conducted by Eccles et al. (2002) with the British orienteering squad reported that orienteering performance predominantly relies on cognitive output, which is perceived to be more important than the physiological component in orienteering. This perspective is further supported by elite orienteers and national orienteering team coaches (Celestino et al., 2015; Macquet et al., 2012). As mentioned in section 2.1.3, increased demand for decision-making was associated with greater activation in ACC while the prefrontal cortex region was responsible for working memory, which is known to be limited in humans (Chai et al., 2018; Martin et al., 2018). Although the neurological correlation between cognitive and physical performance, particularly in working memory, has yet to be identified (Leone et al., 2017), a meta-analytic review suggested that cognitive functions including working memory are influenced by the training status of the population (Scharfen & Memmert, 2019). This reveals that training experience in orienteering may affect how orienteers allocate their cognitive resources for decision-making during orienteering.

To increase the accuracy of the navigation, previous research discovered that orienteers usually employed techniques such as visualizing and simplifying the map while running (Macquet et al., 2012), which underpinned the importance of working memory and multitasking in orienteering. Moreover, navigational ability and rapid decision-making were equally important as these components directly affected the selection of the running route to subsequent checkpoints, influencing the overall exercise intensity of the race and the chance of winning (Creagh & Reilly, 1997; Eccles et al., 2002). This emphasises the exceptional management of cognition functions and physiological output in orienteering. The proposed relationship between physical and cognitive performance in orienteering is illustrated in Figure 2.4. The complex cognitive process represents the high demand for perceptual-cognitive skills in orienteering, demonstrating its influence on the decision-making for physiological output. A systematic review has found that training status directly affected cognitive capacity and highlighted that cognitive skills were as important as physiological output in orienteering (Batista et al., 2020). To elaborate, apart from physiological output, superior cognitive performance can differentiate novice and expert orienteers. Considering the importance of decision-making accuracy and cognitive performance in orienteering, any acute impairment in cognition during orienteering such as MF, may affect the efficiency of managing cognitive recourses and subsequently impair overall orienteering performance.

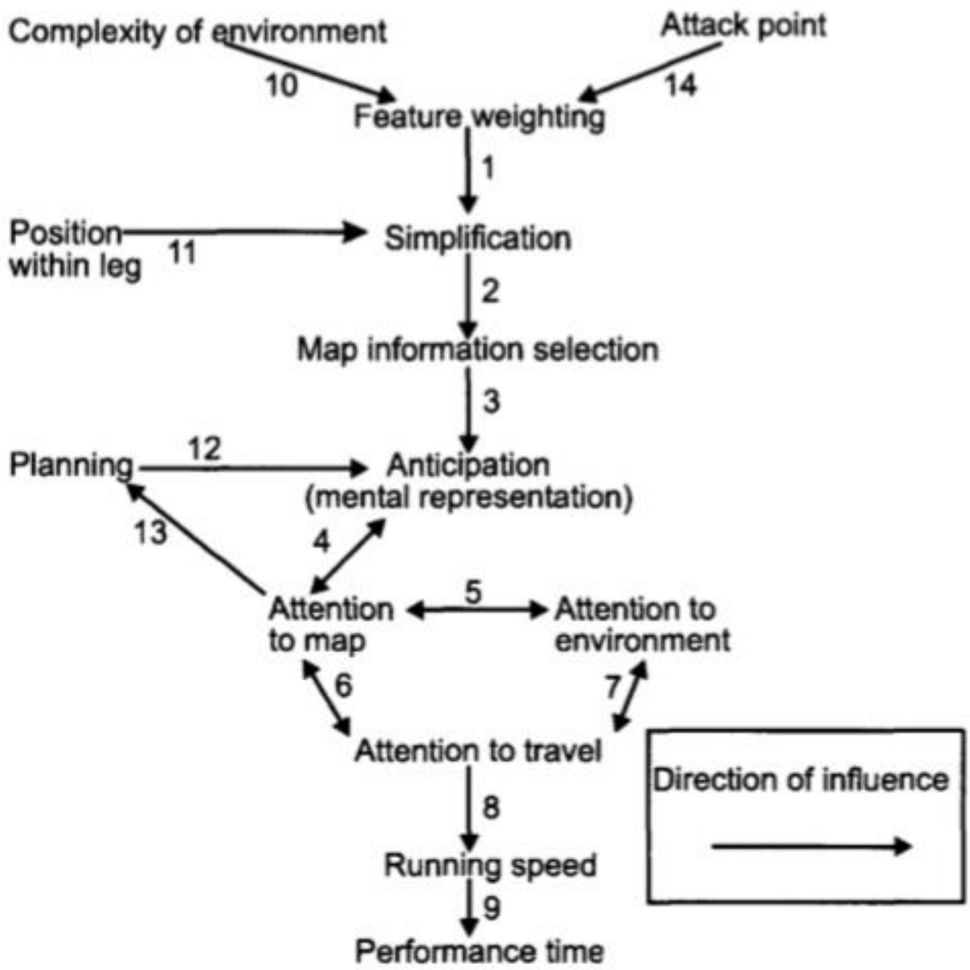

Figure 2.4 The proposed cognitive process of orienteers during a race (Eccles et al., 2002).

Additionally, section 2.6.1 showed the proposed decision-making process during orienteering, where orienteers consider three primary sources of information in creating their tactical plan between each control point: the map, terrain features and navigation (Celestino et al., 2015; Eccles & Arsal, 2015). While running and looking at the map simultaneously, orienteers also examine obstacles, elevation changes, and route distances to evaluate the feasibility of their chosen path, as highlighted by Eccles (2008). Previous research has highlighted that navigating to checkpoints without hazards requires high cognitive effort (Eccles, 2008), reinforcing the importance of multitasking in orienteering, which requires both cognitive and physical outputs. Further explanations on how orienteers use these sources of information will be discussed in sections 2.6.3.2 and 2.6.3.3.

Previous research with 20 recreationally active orienteers and 20 trained orienteers discovered that the trained orienteers spent significantly less stationary time navigating during a 2km orienteering course and achieved a significantly faster completion time compared to the recreationally active orienteers (Eccles et al., 2006a). This suggests that the efficiency of multitasking determines the orienteering performance, highlighting the importance of the cognitive aspect for orienteers. This implies the hypothetical cognitive process presented in Figure 2.4, such as reading the map, identifying surrounding terrain and using navigational equipment, are primarily performed while walking or running, demonstrating the inherent multitasking nature of orienteering. Moreover, orienteers must avoid hazards while running in unfamiliar environments (Eccles, 2006b). The need to think and run simultaneously while allocating substantial attention to their environment underscores the necessity of high cognitive effort to make efficient decisions and ensure decision accuracy during orienteering.

2.6.3.2 Visual Search Behaviour

Orienteering performance relies on the proper balance between physical and cognitive effort, including the accuracy of map interpretation, the speed of decision-making and the efficiency of running, making visual search skills essential for orienteers (Eccles et al., 2006a). According to Figure 2.5, attention to the map and environment is equally important when devising a route to the next checkpoint during orienteering. Moreover, common behaviour strategies were often observed among orienteers when reading the map and searching for identifiable terrain features during the race. One strategy was that orienteers frequently placed their thumb on the approximate location and folded the map to avoid visual distraction (Eccles, 2006b; Eccles & Arsal, 2015; Macquet et al., 2012). This may indicate working memory capacity is limited (Leone et al., 2017), and reveals that the superior cognitive abilities of elite orienteers may be an acute adaptation to the surrounding environment, rather than an expansion of working memory (Macquet et al., 2012; Mann et al., 2007). This behaviour showed orienteers' attempt to minimise visual search while reading, allowing them to focus more on surrounding features while running and navigating in an unknown environment. Furthermore, this strategy may help overcome the limited capacity of working memory by reducing visual search behaviour during orienteering.

However, visual search behaviour may differ depending on the training level of the orienteers. Untrained orienteers tend to remain stationary to locate themselves during an orienteering event, while trained orienteers usually walk or run while planning their route with their compass and map (Eccles et al., 2006a). Moreover, well-trained orienteers focused on the environment rather than the map itself (Eccles & Arsal, 2015). Recent research was conducted utilising an eye-tracking system and found that the distribution of visual fixation was more dispersed in untrained orienteers and more concentrated in trained orienteers during orienteering (Araújo et al., 2019; Liu, 2019). This reflects that trained orienteers have greater efficiency in visual search and potentially better information processing abilities than untrained orienteers.

Regarding the visual search behaviour under the MF state, previous research has yet to find that mentally fatigued youth cyclists had a higher accident rate but it did demonstrate slower response time and a decrease in selective attention, necessitating a longer period of visual fixation in order to respond to potential hazards or mistakes (Zeuwts et al., 2021). Although the study was conducted with children, it offers insight into how a sport such as orienteering that requires rapid and precise decision-making may be negatively affected by the presence of MF. Moreover, given the continuous visual searching behaviour required for orienteering, it is pertinent to investigate the impact of MF on the efficiency of visual information processing, which could lead to poorer orienteering performance. It is important to note that the training status of the orienteer should be taken into account when discussing cognitive function, as it has been shown to influence the variability of visual search behaviour during orienteering (Eccles et al., 2006a).

2.6.3.3 Navigation Skills

It is clear that superior attention focus is necessary for orienteers to conduct a visual search in an unknown environment, however, navigational skills are just as important as they use the information from the visual search to identify the most suitable route to the next checkpoint

(Eccles & Arsal, 2015). The visual search provided orienteers with initial information to navigate themselves on the map in an unfamiliar environment. Previous research has shown that orienteers would visualise the map and carry out an ongoing navigational assessment while running to accurately determine their location (Eccles, 2006b; Eccles et al., 2009), suggesting that navigation and visual search were likely performed simultaneously. This enables orienteers to act quickly when they recognise similar features that match the map or their visualisation, allowing more time to plan their next route choice selection. Previous studies have indicated that orienteers need to use their external attention to identify objects and features in the environment, which they then filter and prioritise the most pertinent information to store in their working memory (Chun et al. 2011). Given that working memory is limited as outlined in section 2.6.3.2 (Leone et al., 2017), this process must be carried out continuously during orienteering until the orienteers reach the finish line. This repetitive navigation process may be a source of cognitive stress in orienteers (Van Cutsem et al., 2017; Martin et al., 2018).

Previous studies have reported both trained and untrained orienteers utilise the most noticeable features of the environment to reduce the cognitive load and simplify the navigation process during orienteering (Eccles, 2006b; Eccles et al., 2006a). However, this simplification strategy does not compromise the precision of decision-making required to reach the next checkpoint. While this simplification strategy may shorten the time taken for map reading, correct navigation is still necessary to ensure that the chosen route is executed accurately. As discussed in section 2.6.3.2, trained orienteers spend less time on visual search while still navigating effectively compared to untrained orienteers. This showed that training adaptations can increase multi-tasking efficiency in orienteering, improving multitasking and information processing with limited working memory resources, and allowing trained orienteers to run and read the map simultaneously. In conclusion, navigation in orienteering heavily relies on environmental cues and is closely linked to visual search ability.

2.6.4 Summary

Orienteering is an outdoor running sport that places substantial demands on both physiological and perceptual-cognitive output (Batista et al., 2020; Creagh & Reilly, 1997). Orienteers need to maintain high levels of concentration to allocate their attentional resources to read the map, interpret their surroundings, and avoid navigational errors. Determining the cognitive demand of orienteering is challenging because the decision-making processes are inextricably intertwined and mutually influential. Inter-individual variation in physiological demand on the same orienteering course is often observed, mainly due to differences in route selection. Cognitive demand is expected to be high due to the repetitive nature of map reading and interacting with the surroundings while running. Well-trained orienteers can seamlessly integrate map reading and running without frequent stops during orienteering, while recreationally active orienteers often have to stop to navigate (Eccles et al., 2006a). This distinction reinforces the importance of the cognitive abilities of orienteers and their connection with the training level. Regardless of training status, it is likely that the increased cognitive demand of orienteering negatively impacts psychophysiological responses compared to the exercise of a cognitive task in isolation. Taken together, the physiological and cognitive output during orienteering is interlinked and should be considered together when assessing the demands of orienteering performance.

As discussed in section 2.2, MF negatively influences both physical and cognitive performance in individual and team sports. Sections 2.6.1 to 2.6.3 demonstrate that orienteering requires continuous and precise decision-making, similar to the cognitive challenges seen in intermittent team sports. Orienteers must constantly interpret maps and react to their environment, making real-time strategic decisions as shown in section 2.6.3.1. Although orienteering shares similarities with intermittent sports, it exhibits fewer extreme fluctuations in both physical and cognitive intensity. Orienteers maintain a steady pace throughout the activity, making gradual adjustments rather than sudden changes. This strategy may lead to a different pattern of MF accumulation compared to team sports. Although the findings in sections 2.2.1 to 2.2.5 on MF in individual and team sports provide valuable insights, they cannot be directly applied to orienteering due to their continuous nature. Moreover, sections 2.6.3.2 and 2.6.3.3 suggest that well-trained orienteers may manage cognitive load and decision-making more effectively than recreationally trained orienteers. Therefore, future research should consider the training status of participants to minimize confounding variables when investigating MF in sports.

2.6.5 Current knowledge of mental fatigue in orienteering

Previous research has shown that orienteers demonstrate slower race completion times when mentally fatigued (Batista et al., 2021), indicating a direct impact of impaired cognitive function on overall orienteering performance. However, there is limited evidence investigating the influence of sustained attention tasks on the physiological responses and cognitive functions of orienteers. To date, although there is limited research specifically examining the impacts of MF on the physical and cognitive variables of orienteering performance, the impaired completion time in subsequent orienteering races following a computerised MF protocol as reported by Batista et al. (2021), suggest that orienteers might be affected by MF, similar to athletes in other sports.

Given the multitasking nature of orienteering (section 2.6.3), which demonstrates a close connection between physical and cognitive outputs as shown in Figure 2.4, it is worthwhile to investigate MF in this sport. Additionally, due to the similarity in cognitive effort required for decision-making between orienteering and intermittent team sports, the potential negative effects of MF on physical (section 2.2.1) and cognitive performance (section 2.2.4) reported among intermittent team sports further support the investigation of MF in orienteering. Moreover, orienteers may exhibit similar impairments in cognitive performance as seen in intermittent team sport athletes (section 2.2.4). Furthermore, section 2.6.3 has demonstrated that orienteering focuses on the precision of decision-making, which explains the impaired orienteering performance identified among mentally fatigued orienteers in Batista et al. (2021). However, rather than building on research findings utilising low-specificity MF protocols as described in section 2.4, it would be important to investigate whether MF occurs naturally during orienteering before further investigating the impacts of MF on orienteering performance. While existing evidence suggests MF may have an impact on orienteering performance, the investigation is in its early stages and has not adequately assessed the impact of MF on orienteering, which is critical given the intricacy of cognitive and physical regulation in orienteering.

2.6.6 Orienteering as a model for studying mental fatigue in sport

While there has been extensive research investigating MF in sports (Brown et al., 2020; Pageaux & Lepers, 2018; Van Cutsem et al., 2017), little attention has been given to sports that largely self-regulated and heavily rely on a combination of physical and cognition effort to perform, such as orienteering. However, Millet et al. (2010) reported that well-trained orienteers could resist cognitive fatigue, enabling them to run efficiently while simultaneously reading the map or performing other cognitive tasks, due to their training adaptation to the high perceptual-cognitive demands of orienteering.

Recent studies reported that mentally fatigued orienteers showed an increase in completion time during a 3.1km orienteering race with an average increase of 2.4 minutes following a 30-minute MF protocol (Batista et al., 2021), implying that MF can be detrimental to sports that require a perfect balance between physical and cognitive effort. Previous research has indicated mentally fatigued individuals tend to be more risk-averse in decision-making (Jia, Lin, & Wang, 2022), which may explain the slower competition times following the MF protocol as orienteers may opt for a less challenging route to reduce the ongoing cognitive stress. This supports the discussion above about the cognitive process of orienteering and highlights impairment in cognition could indeed affect overall orienteering performance. Importantly, as discussed in section 2.2.4, MF can impair the ability to process information quickly, thereby compromising the strategic and tactical performance in intermittent sports. This suggests that sports like orienteering, which require individuals to maintain optimal decision-making ability throughout the race, might be affected by the presence of MF, consequently impacting overall performance. However, further investigation is required to understand the relationship between physiological and perceptual-cognitive performance. As MF is believed to be elicited following cognitively demanding tasks (Van Cutsem et al., 2017), the demands and key role of multitasking in orienteering make it an excellent model for investigating MF to assess whether it naturally arises after the sport, even if athletes are cognitively trained to perform high cognitive load tasks. Previous studies have shown that MF can impair sport-specific decision-making performance as discussed in section 2.2.4 (Sun et al., 2022; Fard et al., 2019; Smith et al., 2016; Kunrath et al., 2020b), raising the importance of understanding how MF might affect decision-making during orienteering. Considering the uniqueness of orienteering where orienteers must effectively manage both physical and cognitive demands, this sport served as an ideal model for studying MF in sports.

Numerous sports, athlete types, faulty methods for MF induction and measurement, and varying outcome metrics all contribute to the obscurity of existing MF research. This complexity makes it difficult to fully comprehend the perspectives of coaches and athletes on MF and whether it is an actual concern in sports. It also presents difficulties in terms of MF detection, measurement, and potential management. Orienteering, a sport that requires a high level of cognitive and physical engagement, can be used as a model to get important insights into the viewpoints of coaches and athletes about mental fitness. This approach offers the chance to investigate whether MF is more likely to appear in a sporting environment. If it does, it also improves our knowledge of how to identify and measure MF.

2.7 Thesis Aims and Objectives

The overreaching aim of this thesis was to investigate the perspectives of orienteering practitioners and athletes on MF and determine whether athletes experience MF as a result of playing the sport. To increase the validity of the results, the thesis seeks to reduce the reliance on laboratory-based research to induce and explain MF. The current thesis conducted three experimental studies to explore MF in orienteering to fill a knowledge gap in the literature. The aims of the experiment are listed below.

***Research question 1**:* How does orienteering practitioners define and recognise mental fatigue?
The aim of experiment 1: To determine the definition, development, cause, influence and methods to reduce MF in orienteering by gathering international orienteering experts consensus.
The hypothesis of experiment 1: Not Applicable.

***Research question 2**:* Does mental fatigue occur during orienteering competition?
The aim of experiment 2: To examine the changes in perceived mental fatigue and other psychological responses during an orienteering competition.
The hypothesis of experiment 2: Not Applicable.

Research question 3: Do junior national orienteers experience mental fatigue during an orienteering training camp?

The aim of experiment 3: To investigate how perceived mental fatigue, mood, and other psychological responses changed during an orienteering training camp in a national squad of junior orienteers.

The hypothesis of experiment 3: Not Applicable.

Chapter 3: General Methodology

All studies in this thesis received ethical approval from the Moray House School of Education and Sport Ethics Committee before participant recruitment and data collection (Appendices A1 - A3.2). Importantly, all experiments were designed to be exploratory, and this thesis did not formulate any hypotheses but rather a research question for each study to enable thorough investigation.

3.1 Methodological Framework

The literature review in this thesis has highlighted the debate regarding the effectiveness of MF induction methods utilised in the literature, criticizing the inability to accurately reflect or replicate the cognitive demand experienced by athletes in sports. The low ecological validity and unstandardised experimental settings reduce the comparability of results and the validity of discussion, limiting our understanding of the MF of athletes. Given the concerns highlighted in section 2.4 regarding the ecological validity of the MF induction methods, it is necessary to investigate MF in a manner that mirrors real-world sports scenarios. The critique of the low specificity of cognitive stressors utilised in laboratory-based experiments to induce MF among athletes as highlighted in section 2.4.2.1, has raised doubts regarding their adequacy for challenging athletes' cognitive resources. Furthermore, the disparity in the perception of MF between athletes and practitioners (Russell et al. 2019), highlights the need for tailored investigations that align with the participants' characteristics. The inclusion of athletes is essential to accurately explain the occurrence of MF in sports. This highlights the importance of recruiting individuals with similar levels of performance and demographic background to enhance the validity of the analysis.

According to the discussion in section 2.3, the development of MF remains unclear, leading to uncertainties regarding its effect on both physical and cognitive performance as outlined in section 2.2. This uncertainty has raised a debate regarding the existence of MF and its potential impact on sports performance. Although previous research demonstrates the successful induction of MF through interventions as reported in section 2.2, the limitations of these interventions discussed in section 2.4.2.1 emphasise the need for a more comprehensive exploration of MF to enhance the applicability of the findings to applied sports contexts. The incomplete understanding of the development of MF constitutes a major barrier to designing MF interventions and providing meaningful recommendations for MF management within the sports context. Following the applied sport science research model in Figure 3.1 (Bishop, 2009), it is essential to improve our understanding of MF before embarking on intervention or management strategies, given the insufficient explanation of MF.

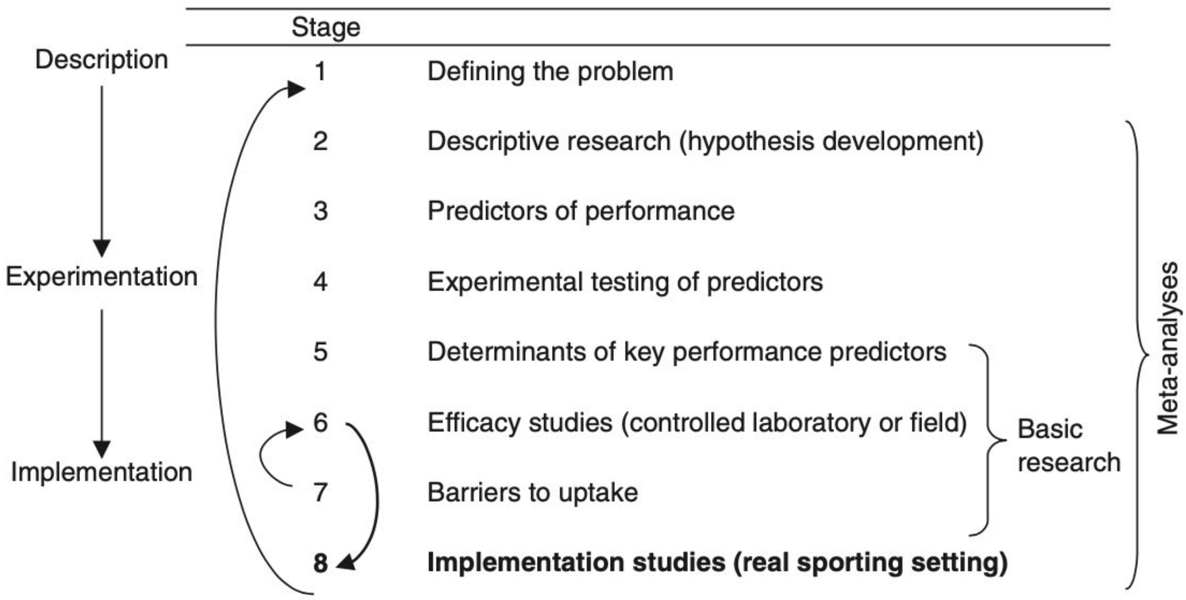

Figure 3.1 The research model for effective exploration in applied sport science (Bishop, 2009).

While laboratory-based study designs such as randomised controlled trials, can effectively increase the internal validity and minimise the risk of Type II error by strictly controlling the environment and health status of the individuals before the experiments (Atkinson & Nevill, 2001). However, it is important to note that real-world sports contexts like training and competitions, introduce variability in external conditions. This reflects the importance of external validity when discussing the generalizability of the outcomes. Although the repeated measures employed during training or competitions introduce less controllable factors compared to laboratory-based experiments, the establishment of standardised data collection methods and the utilization of appropriate measurement tools can yield more ecologically valid findings (Halson et al., 2019; Atkinson & Nevill, 2001). A previous review in performance sports has also emphasised the importance of increasing external validity by employing longitudinal research designs, thereby increasing the generalizability of the findings (Halperin et al., 2018). It is further acknowledged that the high-performance sports population is limited, and utilising longitudinal research designs can reduce sample size requirements while providing an overview of how a small group of athletes changes over an extended period.

However, section 2.4.1 highlighted that previous research predominantly relied on standardised and controlled laboratory-based approaches for investigating MF, with only a limited number of studies employing longitudinal research design to realistically monitor MF changes during pre-season training and competition (Thompson et al., 2020; Russell et al., 2019; Abbott et al., 2018; Abbott et al., 2020). Given the complex nature of MF and potential variability in MF interpretation among individuals, Thompson et al. (2020) adopted a mixed-method approach to collect both qualitative and quantitative data from academy soccer players before and after a soccer match. This approach provided valuable information directly applicable to the applied sports context and assisted researchers in identifying variables relevant to MF. Considering the potential variations in MF interpretation and perception among individuals, together with the distinctive physical and cognitive requirements across different sports, it could be beneficial to adopt a similar mixed-method approach to examine MF in orienteering. This approach can adequately acknowledge the sport-specific aspects of orienteering and accurately characterise MF among orienteers.

In order to facilitate a thorough investigation of MF, the overall research strategy in this thesis involved the following elements:

- Exploring MF induced in a sport-specific context
- Assessing athletes' perceptions of MF
- Using competitive and experienced athletes for the investigations
- Employing mixed methods approaches
- Utilizing longitudinal tracking of athletes to enable observation of the dynamic nature of MF

3.2 Participants

All participants in this research thesis were national-level orienteering athletes and practitioners. The specific numbers and characteristic for each study are displayed in the relevant chapter. Briefly, the inclusion criteria for Chapters 4 to 6 are the following:

Chapter 4 (Study 1):

1. Having at least 10 years' experience in coaching or competing in orienteering.
2. Having represented once as a national team coach or athlete in an international orienteering competition.
3. Having the ability to read and write in English fluently.
4. Having reached the age of 18 or above to complete written consent form.

Chapter 5 (Study 2):

1. Having received regular orienteering training in a national team.
2. Having represented at least once as a national team member in an orienteering competition.
3. Having the ability to read and write in English fluently.
4. Having reached the age of 14 or over to ensure individuals were eligible to receive national-level orienteering training.

Chapter 6 (Study 3):

1. Having received regular orienteering training in a national team.
2. Having the ability to read and write in English fluently.

This thesis refrained from implementing any standardised dietary plan or restricting supplement intake, such as caffeine, before the experiment, to minimise the effect on the participants' regular routines and focus on observing changes in subjective MF and other psychological variables before and after orienteering training or competition. It is important to note that all participants were national-level orienteers, and their diets may already have been prescribed or monitored by their national team nutritionist. Additionally, since the duration of studies 2 and 3 (Chapters 5 and 6) was at least three days, asking the participants to provide a full food diary record could increase their stress levels during an intense racing and training schedule, potentially reducing participant retention. Consequently, no dietary standardisation or records were used in any of the studies.

3.2.1 Recruitment Method and Process

The recruitment in this thesis was primarily performed remotely, except for Chapter 5 which involved a combination of in-person and online participant recruitment. However, all consent forms and parental consent (if applicable) were received electronically via email. All studies in this thesis were conducted remotely using an online survey system (Online surveys, Jisc, UK) or Qualtrics (Qualtrics XM Platform, USA). Participants were asked to provide an email address that they frequently use during the recruitment process to receive the surveys during the experiments. Before commencing the experiment, all participants had to return the completed consent form and parental consent form (if the participants were under the age of 18). The contact details of the researchers and supervisors were available to the potential participants and their parents or guardians during the recruitment process to ensure they were satisfied with the content of the experiments before signing the relevant documents for participation.

Chapter 4 (Study 1)

The expert panel in this study was selected using purposive sampling using the 2019-2020 Orienteering World Ranking List (http://ranking.orienteering.org), with available contact information and the social network of British Orienteering practitioners. A snowball sampling approach was then employed (Kleynen et al., 2014; Price et al., 2020), where the eligible expert panel members were asked to recommend other orienteering experts who met the same criteria as indicated in section 3.2. The lead researcher subsequently conducted an identical screening process for the recommended orienteering experts. Once the participants had fulfilled the inclusion criteria, they received an information package that included the Participant Information Sheet (Appendix B1) and Participant Consent Form (Appendix D1).

Chapter 5 (Study 2)

An invitation email was sent to all orienteers with available contact details on the 2021-2022 Orienteering World Ranking List (http://ranking.orienteering.org/?ohow=F) and British Orienteering national team practitioners. A snowball sampling method was also implemented, where eligible participants were asked to recommend other orienteers with a similar background using the same inclusion criteria. Once the researcher had confirmed the participants fulfilled the inclusion criteria mentioned in section 3.2, they received a pre-experiment package that included the Participant Information Sheet (Appendices B2.1-2.2) and Participant Consent Form (Appendices D2.1-2.2). Additionally, participants under the age of 18 received a Parental Consent Form (Appendices E1.1-1.2), with consent from their parents or guardians obtained prior to participation. All participants returned the completed consent form and parental consent forms, along with the competition date that they considered important, so the survey could be set up accordingly.

Chapter 6 (Study 3)

The purposive sampling method was used to recruit orienteers attending the British Orienteering Talent Squad competition preparation camp. An invitation email was sent to the managers and three super-regions coaches of the British Orienteering Level 3 Talent Squad, who then forwarded the email to their athletes and parents during the preparation phase of the training camp. Given that most of the orienteers in the squad were under the age of 18, an information package was provided once the researcher confirmed that the participants met the criteria outlined in section 3.1 This package contained the Participant Information Sheet (Appendix B3), Parental Information Sheet (Appendix C2), Participant Consent Form (Appendix D3.1) and Parental Consent Form (Appendix E2).

3.3 Online Survey Design

All experiments in this thesis were conducted remotely, with participants utilising their own electronic devices such as smartphones, laptops or tablets to complete the survey within the specified time frame. Given the controversial nature of MF issues in sports and the potential variation in perceptions of MF among individuals, an online survey was considered the most suitable method to promote open discussion. Braun et al. (2021) indicated that an online survey can increase participation, especially for controversial and sensitive topics, as participants can complete the survey privately on their own electronic devices, without the anxiety that may arise during face-to-face interactions. The use of electronic devices for survey completion is effective and efficient in monitoring the health and physical activity of individuals (Buoitestella et al., 2021). Participants were strongly advised to use the same device for both the familiarisation and experimental trials to maintain consistency. The survey designs for each study are displayed in the relevant chapters.

3.3.1 Standardising the Concept of Mental Fatigue Across Studies

As highlighted in section 2.4.3 of this thesis, previous investigations have been criticised for not specifying participants' background knowledge or providing a clear explanation of MF within their studies. This introduces a confounding variable, potentially leading to varying interpretations of MF among participants across different studies. Therefore, this thesis provided the definition of MF that is widely used in the literature by participants (Van Cutsem et al., 2017; Pageaux et al., 2014).

Mental fatigue characterized by feelings of tiredness and a lack of energy and induced by prolonged periods of demanding cognitive activity

This approach to establishing a similar understanding of MF among participants reduces the possibility of confusing MF with other fatigue-related responses and minimises inter-individual differences in the interpretation of MF. In terms of familiarization with the experiments conducted in this thesis, all participants involved in studies 2 and 3 (Chapters 5 & 6 respectively) were instructed to complete a familiarization trial prior to the experimental trial. Since the survey required to be completed within specific timeframes, such as within 30-minutes of waking and immediately after competition or training as identical to previous research (Russell et al., 2022), participants completed the familiarization trial during an orienteering competition (study 2) or training (study 3) to maintain consistency. This approach enabled participants to clarify any uncertainties they may have had in differentiating MF from other psychological responses during orienteering and also reduced the potential learning effects associated with certain measurements. However, familiarisation was deliberately excluded in study 1 as its experimental design differed from studies 2 and 3.

3.3.2 Selection of measurement tools

Following the critical evaluation of the effectiveness and limitations of both objective and subjective measures for MF in sections 2.5.1 to 2.5.3, it is crucial to adopt a combination of both measurement tools to investigate MF. Reaction time and response accuracy were selected as objective indicators of MF. This thesis acknowledges the complexity of understanding MF, as discussed in sections 2.5.1.1 to 2.5.1.6, and utilises a bipolar anchor to help differentiate various psychological response variables. Based on the discussion in section 2.5.2, the 100-

mm VAS and the BRUMS were selected as subjective measurements to assess MF and other psychological responses.

In this thesis, both bipolar and unipolar scales were utilised. The bipolar scale, primarily used in Chapter 4, ranged from "strongly disagree" to "strongly agree", offering the necessary sensitivity and precision to capture variations in agreement levels (Pilgrim et al., 2018; McCall et al., 2020; Diamond et al., 2014; Hsu & Sandford, 2007). This format enabled experts to express subtle distinctions in their evaluations, which was essential for refining subsequent rounds of the survey. Furthermore, it provided space for open-ended comments, providing experts the opportunity to elaborate on their reasoning for disagreement. The use of a bipolar scale in the Delphi study was particularly advantageous as it captured both agreement and disagreement, facilitating a more nuanced and comprehensive assessment than a unipolar scale.

Conversely, unipolar scales were primarily used in Chapters 5 and 6. The VAS employed in this thesis utilised unipolar anchors, aligning with those commonly used in psychological assessments in similar observational research with elite netballers (Russell, 2021; Russell et al., 2022). This design facilitated a clearer understanding of MF and helped differentiate between various psychological responses. Given the limited understanding of MF and the discrepancies in existing literature (sections 2.1.4 and 2.3), the implementation of clear, evidence-based anchors aimed to improve respondents' interpretation of MF, thereby enhancing the accuracy and reliability of subjective measurements in this context.

3.3.2.1 Congruent and Incongruent Stroop task

Although section 2.5.3 concluded that implementing sport-specific reaction time and response accuracy assessments could increase the validity of findings, the author was unaware of the existence of an orienteering-specific executive function test in the literature. Despite the low specificity in assessing reaction time and response accuracy in orienteers, this thesis acknowledged the extensive use of a Stroop task in MF research as discussed in sections 2.5.1.1 and 2.5.1.2. Using a Stroop task as an objective indicator of MF can help increase the comparability of findings. The congruent and incongruent Stroop task has demonstrated acceptable test-retest reliability ($r = 0.67$ to 0.77)(Graf et al., 1995). Similar to previous MF research (Fortes et al., 2020; Fortes et al., 2021), the Stroop task was implemented to assess the executive function before and after orienteering participation. The Stroop task was integrated into the survey and completed by participants on their own electronic devices. Further details and instructions regarding the task are outlined in section 5.2.

3.3.2.2 100-mm Visual Analogue Scale

Building on the discussion in section 2.5.2.3, it was concluded that the 100-mm VAS is the most appropriate subjective measure for MF, supporting the suggestions of Smith et al. (2019). Given the limited understanding of MF development, it becomes essential to monitor other subjective fatigue-related responses to further contextualise the changes in MF, as discussed in the literature review of this thesis. The 100-mm VAS has been frequently used to measure subjective fatigue-related responses in MF research, as highlighted in the literature review of this thesis. Furthermore, this scale has demonstrated high validity and reliability when assessing fatigue-related responses in healthy populations during both morning and evening periods (α = 0.91 to 0.96)(Lee, 1991). To minimise potential misinterpretations and comprehensively evaluate the effect of MF, this thesis adopted the fatigue-related self-report variables utilised in previous observational research with elite netballers, including motivation, physical fatigue, stress, tiredness and sleep (Russell et al., 2021; Russell et al., 2022). These variables were measured using the 100-mm VAS. Monitoring changes in these psychological responses provides additional insights into the relevance of MF to these variables. Given the inconsistencies and lack of standardised anchors and questions highlighted in section 2.5.2.3, which impairs the comparability and interpretation of MF in sports, this thesis employs standardised questions and descriptors for the variables measured via the 100-mm VAS, as displayed in Table 3.1.

Table 3.1 The question and descriptor for the 0-100 self-report slider scale.

Measure	Question	Anchor for 0	Anchor for 100
Mental fatigue	What is your current level of mental fatigue?	Mentally fresh	Mentally exhausted
Motivation	How motivated are you to complete your next orienteering race?	None at all	Highly motivated
Sleep quality*	How would you rate your sleep quality last night?"	Very poor	Excellent
Physical fatigue	What is your current level of physical fatigue?	Physically fresh	Physically exhausted
Stress	What is your stress level right now?	Very relaxed	Highly stressed
Tiredness	How tired are you right now?	Very alert	Extremely tired

* The question only occurs in the survey that to be completed in the morning.

3.3.2.3 The Brunel Mood Scale

In addition to assessing fatigued-related variables to understand the effects of MF in sports, it is important to consider mood responses particularly the vigour and fatigue subscale of the BRUMS, which are negatively affected under MF conditions as highlighted in section 2.5.2.2. The BRUMS has demonstrated good internal consistency and reliability ($\alpha = 0.85$) when assessing mood states among healthy populations (Brandt et al., 2016). To evaluate the effect of MF on the multifaceted mood dimension, this thesis also integrated the BRUMS to measure the mood state of orienteers in studies 2 and 3 (Chapters 5 & 6).

3.4 Statistical analysis

3.4.1. Evaluation of statistical approaches

3.4.1.1 Null hypothesis significance testing (NHST)

It is acknowledged that NHST is a widely utilised statistical analysis method in sports science research (Harrison et al., 2020). The consistent usage of NHST increases the comparability of findings because the p-value provides evidence for either accepting or rejecting the null hypothesis. However, NHST has several major limitations that may reduce the validity of findings. Statistical significance ($p < 0.05$) does not necessarily equate to practical or clinical significance, as p-values do not provide information about the magnitude of observed changes

(Harrison et al., 2020). Therefore, overreliance on statistical significance can lead to misleading interpretations of the true effect of changes. NHST primarily uses p-value to indicate whether significant differences exist between time points or groups (Harrison et al., 2020; Turner et al., 2021). It is important to recognise that p-values are sensitive to the sample size, with greater variability in studies with fewer participants (Harrison et al., 2020; Wasserstein et al., 2019). NHST with small sample sizes can yield underpowered analyses, labelling small effects as statistically significant despite their lack of practical relevance. Consequently, failing to reject the null hypothesis does not necessarily represent an absence of effect but rather insufficient statistical power. This issue is particularly pertinent in sports-related research due to the limited availability of Tier 3 to 5 athletes (McKay et al., 2021), leading to smaller sample sizes. Research employing NHST to examine Tier 3 to 5 athletes may fail to demonstrate practical significance.

Another limitation is that NHST requires an extensive theoretical framework, with researchers required to formulate null or alternative hypotheses before conducting the experiment. This requirement can restrict its applicability in exploratory or natural phenomena-based studies. Due to these characteristics, NHST is considered more suitable for investigation aiming to determine cause-and-effect relationships (Harrison et al., 2020; Turner et al., 2021). To conclude, NHST might not be an ideal approach to investigating MF due to the limited understanding of how and when MF occurs in orienteering. Researchers may face challenges in designing appropriate research methodologies and formulating hypotheses suitable for NHST.

3.4.1.2 Magnitude-based inference (MBI)

In contrast to NHST, the MBI places greater emphasis on practical significance over statistical significance, aiming to provide insights into the real-world relevance and magnitude of effects. However, MBI has encountered substantial criticism due to the lack of a universal standard for interpreting its results. This has led to varying subjective interpretations and inconsistent reporting unlike NHST, which provides a standardised indicator for reporting significant changes (Lohse et al., 2020; Sainani et al., 2019). Previous research indicates that while MBI may reduce the Type II error rate, it also increases the Type I error rates by 12% to 22% for the sample size of 8 and by 22% to 45% for sample sizes of 15 (Lohse et al., 2020; Harrison et al., 2020). This increased Type I error rate can lead to the exaggeration of findings and introduce bias. The lack of universally established thresholds for interpreting MBI findings further contributes to the potential misinterpretation, as MBI primarily focuses on the point estimate of an effect without adequately considering the associated uncertainty. Given the absence of standardised practical significance and the potential for inadequate reporting, MBI was not employed in this thesis.

3.4.1.3 Delphi Methodology

The Delphi study is a statistical method used to develop a consensus based on input from a group of experts (Hsu & Sandford, 2007), and its findings can provide valuable direction for future research. While there may be concerns about selection bias, it is important to note that participants in this study were selected based on strict criteria, as detailed in Section 3.2. This approach aligns with other Delphi studies (McCall et al., 2020; Kleynen et al., 2014; Price et al., 2020), ensuring the development of a robust consensus that can effectively guide further research. One major concern with the Delphi technique is the threshold for agreement. The percentage range used to define consensus varies across the literature (Diamond et al., 2014; Hsu & Sandford, 2007), leading to variability in how consensus is interpreted. While a systematic review has reported a median agreement threshold of 75%, with a range from 50% to 97% (Diamond et al., 2014), it is generally accepted that a Delphi study requires a minimum of 70% agreement on a statement to establish consensus (Hsu & Sandford, 2007; McCall et al., 2020). Furthermore, some studies with smaller sample sizes have utilised a consensus threshold of 65% (Engelman et al., 2018; Dribin et al., 2021).

One of the major concerns in Delphi studies is determining the appropriate number of survey rounds. There is ongoing debate about whether termination should occur after completing a specified number of rounds or once consensus on particular statements has been achieved. However, a systematic review of 100 Delphi studies found that 71.4% specified the number of rounds before the study commenced, with nearly half using 2 rounds and 42 studies using 3 rounds (Diamond et al., 2014). Conversely, only 23.5% of the studies terminated the Delphi study upon reaching consensus on the targeted statements (Diamond et al., 2014). This finding suggests that most Delphi studies terminate after a pre-specified number of rounds, and that two rounds are most common.

Another important consideration in addition to defining the maximum number of survey rounds, is establishing clear criteria for excluding statements when consensus is not achieved (Hsu & Sandford, 2007; Diamond et al., 2014). This is crucial as it directly influences how the overall findings are interpreted by the researchers. When a statement fails to reach consensus after two consecutive rounds, it is considered to have not achieved consensus and is excluded from further analysis (Hsu & Sandford, 2007). Consequently, it may be regarded as fundamentally irrelevant to the study's objectives or not aligned with the collective understanding of the expert panel.

According to a previous systematic review, there are no validated quality indicators for Delphi studies (Diamond et al., 2014), which may undermine the validity of their findings. However, it is crucial to note that the expert panels in Delphi studies are carefully selected, with the primary aim of gathering expert perspectives on topics where current evidence is limited. Therefore, the absence of validated quality indicators should not diminish the effectiveness and validity of the Delphi methodology. To enhance the validity of Delphi study findings, researchers should clearly define the agreement threshold, the maximum number of survey rounds, and set criteria for excluding statements.

3.4.1.4 Recommendation

While this thesis identifies the limitations of previous MF investigations, particularly regarding the prior MF knowledge of participants (sections 2.1.4, 2.4.3, and 2.5.2.4), these factors may influence the interpretation of results and potentially introduce confounding variables. Section 3.3.1 proposes that participants should possess a similar foundational knowledge of MF before the commencement of the experiment to increase the validity of the measurements. However, as discussed in sections 2.1.4, 2.4.3, and 2.5.2.4, interpretation and understanding of MF can vary significantly between individuals and across different occupations, highlighting the need for a more precise definition.

Given the insufficient understanding of MF development, as discussed in sections 2.1.5 and 2.3, and the varying interpretations and resistance to MF observed among different individuals and occupations (Russell et al., 2019; Smith et al., 2019), a Delphi approach which gathers consensus from experts in a specific field through multiple survey rounds would be beneficial (section 3.4.1.3). This approach can improve our understanding of MF within sports and provide a solid foundation while addressing the varying interpretations of MF across different sports (Russell et al., 2019; Smith et al., 2019). Specifically, this thesis focuses on elite orienteers, aligning with the Delphi study's nature in gathering expert consensus. This approach could reasonably increase the specificity of subsequent investigations in this thesis. According to the discussion in section 3.4.1.3, it is advisable to use at least 70% consensus over three rounds to allow for a thorough investigation of expert opinions.

Based on the discussion in sections 3.4.1.1 and 3.4.1.2, conventional statistical analysis has both strengths and limitations. To increase the real-world relevance of the findings, this thesis exclusively recruited elite orienteers as reported in section 3.2. Given the challenges of obtaining a large sample size of elite athletes for sports science research, this thesis opted not to employ NHST. The rationale was based on the acknowledgement that small sample sizes can introduce biases in NHST outcomes. A key concern was the sensitivity of the p-value to sample size, which could lead to overestimation of results. While the measurement of practical significance through the MBI approach could address some of the limitations of NHST, it presents a major drawback of MBI: the high risk of bias, as mentioned in section 3.4.1.2. Following recommendations from previous research, this thesis refrained from using NHST and employed the analysis of effect size (ES) and confidence intervals (Cumming, 2012; Calin-Jageman & Cumming, 2019). This approach emphasises interpreting ES with confidence intervals in pairwise comparisons rather than relying on statistical significance. Previous research reports that providing a well-established threshold for ES and presenting it alongside confidence intervals addresses the uncertainty associated with findings (Harrison et al., 2020), thereby increasing the robustness of the explanation. This approach helps mitigate the limitations associated with the small sample size in this thesis and promotes the practical significance of the findings.

3.4.2 General data analysis methods and interpretation

Following a thorough evaluation of the statistical analysis, this thesis primarily employed ES and confidence intervals (CI) for the data analysis. All qualitative and quantitative data were exported to Microsoft Excel. For quantitative data analysis, data were presented as mean ± standard deviation (SD) unless otherwise specified. The magnitude of changes in paired comparisons was calculated using ES together with 95%CI via Exploratory Software for

Confidence Intervals (Version 1)(Cumming, 2012). Previous research has criticised the traditional interpretation of Cohen's d ES could potentially overestimate the effects of the results in sports science research due to the small participants number (Hopkins 2009). Therefore, in this thesis, the ES was interpreted as the following: trivial (0.00 to 0.19), small (0.20 to 0.59), moderate (0.60 to 1.19), large (1.20 to 1.99), very large (2.00 to 3.99) and extremely large (≥ 4)(Batterham & Hopkins, 2006; Hopkins et al., 2009). The following equation was used to calculate the ES in this thesis:

$$d = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2 + s_2^2}{2}}}$$

For qualitative data analysis, a summative content analysis with two-step analysis was employed to identify keywords and form clusters where the keywords were identified to generate a relevant concept and then a theme was created to form a cluster (Cote et al., 1993; Hsieh et al., 2005). The relevant details of the statistical tests utilised in each study were displayed in the relevant chapters.

This thesis also adopted additional statistical methods to address individual variability and the non-independence of repeated measures. Previous research has highlighted the importance of utilizing mixed models for analysing observational and longitudinal data in sports science research (Newans et al., 2022). To handle the estimation of uncertainty and account for the non-independence of multiple observations in a repeated measures study involving the same participants, a linear mixed model (LMM) with restricted maximum likelihood was utilised. The participants' identities were included as random intercept factors to account for intra-individual dependencies and inter-indivudal heterogeneity. The gender and time point of the measurements were used as the estimation of fixed effects. To identify the optimal model, the random intercept models and various random slope models were tested and compared using Akaike's Information Criterion (AIC) and likelihood ratio test (LRT), ensuring the model selection was the best fit while considering convergence issues. The Bonferroni post-hoc analyses were applied to control Type I error for multiple comparison when signifciant effects ($p < 0.05$) were reported. All analyses were completed using the GAMLj model in Jamovi (Version 2.3, The Jamovi Project)(Sahin & Aybek, 2020) and "lme4" in R studio (Version 4.4.2, RStudio).

Chapter 4: Perceptions of Mental Fatigue from International Orienteering Experts

The abstract of this chapter has been accepted and presented at the British Association of Sport and Exercise Sciences (BASES) Conference 2021 (Poster presentation).

International Experts Consensus on the Development of Mental Fatigue in Orienteering: A Delphi study

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4.1 Introduction

Orienteering is a running sport that requires individuals to navigate through unfamiliar terrain using a compass and map, making rapid deicisons about the most efficient route to checkpoints (Batista et al., 2020; Eccles, Walsh, & Ingledew, 2002). According to previous systematic reviews, the HR of trained and national orienteers typically ranges between 150 and 200 beat.min^{-1} during competitions (Batista et al., 2020; Creagh & Reilly, 1997). For example, national-level orienteers have an average HR of 167 beat.min^{-1} while running and navigating terrain that consists of incline, decline and horizontal surfaces (Creagh & Reilly, 1997). The duration of an orienteering competition can vary from 25 to 90 minutes, depending on the type of competition (Creagh & Reilly, 1997). There are five types of orienteering competitions: knockout sprint, relay, sprint, middle-, and long-distance, with estimated distances ranging from 1km to 16km (https://eventor.orienteering.org/Events). The distance covered by orienteers varies as they use their compass and map to identify the most efficient route to each checkpoint based on their physical capabilities. The conscious decision-making process in orienteering is complex, as it requires orienteers to recognise and interpret surrounding environmental features (Batista et al., 2020; Creagh & Reilly, 1997). Although endurance athletes tend to show greater resilience to MF during physical activity (Holgado, Zabala, & Sanabria, 2019; Martin et al., 2016), it remains unclear whether the dual-tasking nature of orienteering might lead to MF. Investigating MF in orienteers is important due to the noticeable physical and cognitive load required in the sport. Previous systematic reviews and section 2.2.4 have concluded that MF negatively affects the accuracy of technical decision-making in sports (Cao et al., 2022; Sun et al., 2022). In orienteering, missing a checkpoint can result in disqualification, which highlights the importance of maintaining focus and making precise decisions throughout the race. Given its lengthy duration and high cognitive demand, orienteering is an ideal sport for investigating the effects of MF. To date, only one study has specifically investigated MF in orienteering. Batista et al. (2021) found that well-trained orienteers completed a simulated orienteering race more slowly when mentally fatigued. This suggests that a decrease in cognitive abilities due to MF directly affects orienteering performance, aligning with findings in Mann et al. (2007) which showed the importance of cognitive ability in orienteering.

MF is a negative change in the psychobiological state following a prolonged period of cognitively demanding activity (Lam et al., 2021). The literature review in this thesis and recent meta-analyses and systematic reviews (Giboin & Wolff, 2019; Habay et al., 2021; Van Cutsem et al., 2017) demonstrates that most investigations utilised lengthy and static computerised mentally challenging tasks to induce MF, resulting in impairments in subsequent endurance and decision-making performance. Although subjective ratings are considered the most reliable way to measure MF (Smith et al., 2019), there is ongoing debate about the ecological validity of these experimental models in understanding the presence, development and effects of MF in sports. While many studies has focused on the acute effects of MF, a recent investigation reports that MF may also be experienced chronically during extended periods, such as a 5-day training camp or an 8-15 day race schedule (Russell et al., 2021). Another investigation involving elite female netballers over a 16-week pre-season training period demonstrated that subjective ratings of MF were significantly higher from week 12 onwards, supporting the argument for chronic MF in sports (Russell et al., 2022). This implies that MF can accumulate over time rather than being triggered by a single mentally demanding task only. Previous research has concluded that perceived mental and physical fatigue are distinct constructs (Russell et al., 2019), with a significant relationship between readiness to perform and perceived MF (Russell et al., 2022). Consequently, future investigations should consider both the acute and chronic development of MF when examining its impact on sports performance.

There is increasing evidence that elevated perceived MF can impair endurance running and decision-making performance in laboratory-based experiments, even though no significant were observed in physiological markers such as HR and blood lactate (Giboin & Wolff, 2019; Habay et al., 2021; Van Cutsem et al., 2017). The ecological validity of these findings has been criticised due to the reliance on an artificial MF protocol, which may not reflect the complexities of an acutal sporting environment (Brown et al., 2020; Giboin & Wolff, 2019; Habay et al., 2021; Van Cutsem et al., 2017). These simplified approaches might result in an oversimplified understanding of the effect of MF on sports performance. Coutinho et al. (2017) is the only study to employ a football-specific MF protocol, addressing issues highlighted by Thompson et al. (2019), such as discrepancies in cognitive and physical demands in existing laboratory-based experiments when investigating MF in football.

In addition to unresolved issues of the definition of MF mentioned in section 2.1.5, Russell et al. (2019) explored how elite netball athletes and practitioners perceive MF. This emphasised the importance of a population-specific understanding of MF, as the unique demands of each sport may result in different perceived causes and impacts of MF. This further emphasises the importance of examining the understanding of MF within a specific sports context before examining its impacts on sports performance. Moreover, it is also critical to explore sport-specific cognitive variables that contribute to MF. Given the ongoing debate over the definition and impact of MF in sports, the development of MF remains controversial (Martin et al., 2018; Smith et al., 2018). To clear this uncertainty, future research should consider consulting experts through a Delphi study because this research method can bridge gaps in practical knowledge when empirical evidence is limited or unclear due to technological difficulties (Hsu & Sandford, 2007; Verhagen et al., 1998).

To optimise the experimental design of MF research, it is necessary to gain a better understanding of the presence of MF in sports, particularly from the perspectives of practitioners and athletes. Given the physical and cognitive demands involved in orienteering, orienteering serves as an excellent model for investigating MF. The aim of this research was to gain insights from international orienteering experts on the definition, development, causes, impact and methods for reducing MF in orienteering.

Research Question: How does orienteering practitioners define and recognise mental fatigue?

4.2 Methodology

Steering Committee

The Delphi survey was initially established by the lead researcher. The survey was then reviewed by three researchers with backgrounds in exercise physiology and performance psychophysiology, as well as a steering committee to guarantee the appropriate use of terminology. The steering committee consisted of two national-level orienteering coaches and athletes with a background in sports science, along with one sports psychologist with expertise in cognition-related research.

Expert panel

The selection criteria of the participants are outlined in section 3.2. Twenty-four orienteering experts provided their informed consent and agreed to be involved in this research. However, six experts were unable to participate as they failed to respond to the survey invitations and reminders within two weeks: five during the second round and one during the third round. The characteristics of the expert panel are shown in Table 4.1.

Table 4.1 The demographics and characteristics of the orienteering experts.

Categories	Round 1 (n = 24)	Round 2 (n = 19)	Round 3 (n = 18)
Gender:			
Male	16 (66.7%)	13 (68.4%)	12 (66.7%)
Female	8 (33.3%)	6 (31.6%)	6 (33.3%)
Currently based (country):			
Canada	1 (4.2%)	N/A	N/A
Denmark	1 (4.2%)	1 (5.3%)	1 (5.6%)
Finland	1 (4.2%)	1 (5.3%)	1 (5.6%)
France	2 (8.3%)	2 (10.5%)	2 (11.1%)
Italy	2 (8.3%)	1 (5.3%)	1 (5.6%)
Norway	2 (8.3%)	2 (10.5%)	2 (11.1%)
Russia	1 (4.2%)	1 (5.3%)	1 (5.6%)
Sweden	4 (16.7%)	3 (15.8%)	3 (16.7%)
Switzerland	3 (12.5%)	2 (10.5%)	2 (11.1%)
United Kingdom (England, Scotland, Wales)	7 (29.2%)	6 (31.6%)	5 (27.8%)
Country of practice:			
Australia	1 (4.2%)	1 (5.3%)	1 (5.6%)
Canada	1 (4.2%)	N/A	N/A
Denmark	1 (4.2%)	1 (5.3%)	1 (5.6%)
France	3 (12.5%)	3 (15.8%)	3 (16.7%)
Italy	2 (8.3%)	1 (5.3%)	1 (5.6%)
Norway	2 (8.3%)	2 (10.5%)	2 (11.1%)
Sweden	1 (4.2%)	1 (5.3%)	1 (5.6%)
Switzerland	3 (12.5%)	2 (10.5%)	2 (11.1%)
United Kingdom (England, Scotland, Wales)	8 (33.3%)	6 (31.6%)	5 (27.8%)
Multi-location (more than one country)	2 (8.3%)	2 (10.5%)	2 (11.1%)
Primary role in Orienteering:			
Athlete	13 (54.2%)	10 (52.6%)	10 (55.6%)
Former Athlete	4 (16.7%)	4 (21.1%)	4 (22.2%)
Orienteering Coach	7 (29.2%)	5 (26.3%)	4 (22.2%)
Years of experience in Orienteering:			
Athlete & Former athlete	16.2 ± 7.27	16.4 ± 7.76	16.4 ± 7.76
Orienteering Coach	16.7 ± 7.16	17.8 ± 7.33	18.8 ± 8.1
Involvement in orienteering*			
As a coach:			
Sprint Distance	7 (29.2%)	4 (21.1%)	4 (22.2%)
Middle Distance	9 (37.5%)	7 (36.8%)	6 (33.3%)
Classic/ Long Distance	9 (37.5%)	7 (36.8%)	6 (33.3%)
Relay	7 (29.2%)	5 (26.3%)	5 (27.8%)
As a competitor:			
Sprint Distance	20 (83.3%)	15 (78.9%)	14 (77.8%)
Middle Distance	22 (91.7%)	17 (89.5%)	16 (88.9%)
Classic/ Long Distance	23 (95.8%)	18 (94.7%)	17 (94.4%)
Relay	23 (95.8%)	18 (94.7%)	17 (94.4%)

N/A: Not available; * Experts were allowed to select more than one answer.

Procedure

Three surveys were conducted using the online survey system (Online surveys, Jisc, UK). The opening page of each survey provided participants with information on the aim of the survey, along with instructions on how to complete it. The surveys were all composed of the same sections, in the following order: (1) the definition of mental fatigue, (2) the development of mental fatigue, (3) the causes of mental fatigue, (4) the impacts of mental fatigue on orienteering, and (5) the methods to reduce mental fatigue in orienteering. Participants could answer each survey in any order they wished within two weeks; however, they were advised to complete it in one session to maintain consistency.

To facilitate relevant discussion as reported by Russell et al. (2019), questions for the first round were developed following the literature view of this thesis. The objective of Round 1 was to explore whether the existing evidence is in line with the experience of practitioners and to identify the aspects deemed relevant to the identified themes. Given that the Delphi study sought to gather consensus through a structured method (Hsu & Sandford, 2007), the items in each subsequent round were based on the findings and summative feedback from the previous round. The expert panel was asked to provide justification for their ratings and provide suggestions for further discussion regarding the questions, which were used to assist in the design of the subsequent survey round. In rounds two and three, the lead author summarised and transformed the collected open-ended responses to create the questions for the subsequent rounds. The lead author also amended the questions to guarantee specificity for the orienteering population, as advised by the steering group committee before launching each survey round. The questions and items in surveys rounds two and three were derived from the results and analysis of the previous round. The survey also integrated some of the responses from the previous round. Rounds 2 and 3 of the survey allowed the expert panel to make further refinements to their assessments of the items.

For the issues that required consensus, the experts were asked to answer the posed questions or statements by selecting a 'Yes or No' option or by using a 5-point Likert scale (0-4), where 0 indicated "Totally disagree", 1 indicated "Disagree", 2 indicated "Neutral", 3 indicated "Agree" and 4 indicated "Totally agree". Furthermore, they were urged to explain their answer in the open-ended question following the ratings. According to the discussion in section 3.4.1.3, this research adopted a consensus threshold of at least 70% agreement among the expert panels, in adherence with previous Delphi studies with the number of participants less than 50 (Hsu &

Sandford, 2007; Kleynen et al., 2014; McCall et al., 2020). If the expert panel achieved a consensus of ≥ 70%, no further questions were asked, unless the expert panel raised any additional issues in their open-ended responses. The items with less than 70% agreement were reworded or amended according to the open-ended responses of the expert panel via two-step qualitative analysis (Cote et al., 1993; Hsieh & Shannon, 2005). To ensure valid consensus-building in the Delphi study (Diamond et al., 2014; Hsu & Sandford, 2007), if the response rate for a question or statement remained below 70% after two survey rounds, the question was deemed to have 'no consensus' and removed from any further rounds (McCall et al., 2020). The expert panel was given two weeks to finish every round of the survey followed by 4-6 weeks for the examination of responses and the planning of each subsequent survey round as suggested (Hsu & Sandford, 2007).

Statistical Analysis

The expert panel responses were exported to Microsoft Excel for descriptive and content analysis. The response rate of the surveys and the extent of agreement were presented as a percentage. To evaluate the responses given on a 5-point Likert scale, the frequency of responses was translated into a percentage to identify the extent of consensus. For the open-ended responses, a summative content analysis was conducted by recognising the keywords to produce a relevant concept and creating a theme to form a cluster. This two-step analysis and interpretation is recommended for analysing qualitative data (Cote et al., 1993; Hsieh & Shannon, 2005).

4.3 Results

The initial round of the Delphi survey was distributed on 8th March 2021 and the final round of the survey terminated on 20th June 2021.

Round 1

All 24 expert panel members took part in the first survey, with a 100% response rate. The main results of this survey are listed in Table 4.2, with 11 out of 19 items using a 5-point Likert scale and two questions being answered with yes or no achieving a consensus. Most (i.e. 91.7%) of the expert panel agreed that they experience mental fatigue in their everyday lives and there was absolute agreement that it exists in orienteering (i.e. 100%). The definition of mental fatigue that didn't reach consensus was eliminated, and the comments on that definition were used to revise the definition in the next round.

Table 4.2 The descriptive summary of the responses from 24 orienteering experts who participated in the survey during the first round.

Statements	Totally disagree	Disagree	Neutral	Agree	Totally agree	Consensus
The Definition of Mental Fatigue						
"*Mental fatigue characterized by feelings of tiredness and a lack of energy and induced by prolonged periods of demanding cognitive activity*" Do you agree this definition reflects its influence on physical performance in orienteering?	0%	0%	4.2%	58.3%	37.5%	Yes
"*Mental fatigue is induced by the prolonged cognitive task that heightened perception of physical effort independent of changes in cardiorespiratory (aerobic capacity), metabolic and/or neuromuscular responses*" Do you agree this definition reflects its influence on physical performance in orienteering?	0%	20.8%	25.0%	37.5%	16.7%	No
The Development of Mental Fatigue						
The mental fatigue you experienced during orienteering training is the same as the one you experienced during in orienteering competition?	4.2%	33.3%	37.5%	20.8%	4.2%	No
The Cause of Mental Fatigue						
Multitasking in orienteering is cognitively demanding (i.e Read the map, react to the surrounding environment, run on the terrain)?	0%	0%	4.2%	16.7%	79.2%	Yes
Psychological stress will increase the levels of mental fatigue in orienteering, i.e. mood changes due to the external pressure at competition.	4.2%	4.2%	4.2%	33.3%	54.2%	Yes
Physical fatigue and mental fatigue will increase simultaneously	8.3%	16.7%	50.0%	12.5%	12.5%	No
The Impacts of Mental Fatigue						
The conscious decision-making ability of the orienteers is likely to be affected by mental fatigue.	0%	0%	4.2%	29.2%	66.7%	Yes
The following characteristics are likely to be impaired by mental fatigue in orienteering:						
- Endurance performance (ability to maintain an appropriate pacing strategy during orienteering)	0%	20.8%	16.7%	50.0%	12.5%	No
- High speed running performance (ability to run in a high-speed during orienteering)	4.2%	8.3%	29.2%	33.3%	25.0%	No
- Rating of perceived exertion (Subjective feelings towards the loading of the physical task)	0%	4.2%	16.7%	41.7%	37.5%	Yes
- Subjective rating of tiredness	0%	4.2%	12.5%	37.5%	45.8%	Yes
- Reaction (decision) time	0%	0%	0%	41.7%	58.3%	Yes
- The accuracy of decision-making (ability to plan your route/tactics effectively)	0%	0%	4.2%	25.0%	70.8%	Yes
Mental fatigue induces negative psychological changes in orienteering.	0%	8.3%	8.3%	50.0%	33.3%	Yes
The development of mental fatigue in orienteering is related to the duration of the task.	0%	12.5%	20.8%	37.5%	29.2%	No

Table 4.2 Continued.

Statements	Totally disagree	Disagree	Neutral	Agree	Totally agree	Consensus
The extent of mental fatigue experienced in orienteering is dependent on the amount of cognitive effort required to complete the event.	0%	0%	8.3%	37.5%	54.2%	Yes
<u>The Methods to Reduce Mental Fatigue in Orienteering</u>						
The fitter an athlete become, the better resistant to mental fatigue in orienteering.	4.2%	8.3%	33.3%	33.3%	20.8%	No
In orienteering, the development of mental fatigue can be delayed through training adaptation.	0%	0%	0%	50.0%	50.0%	Yes
Mental fatigue is more likely to have a negative effect on psychological processes than physiological capacity (e.g. cardiovascular response) in orienteering.	4.2%	8.3%	20.8%	45.8%	20.8%	No

Round 2

In the second round, 19 expert panel members finished the survey (79% response rate). A content analysis of the qualitative data from open-ended responses in the first round resulted in 20 questions containing 65 items. Of these 65 items, 44 achieved a consensus (70% agreement) in the second round, as demonstrated in Table 4.3.

Table 4.3 The descriptive summary of the responses from 19 orienteering experts who participated in the survey during the second round.

Statements	Totally disagree	Disagree	Neutral	Agree	Totally agree	Consensus
The Definition of Mental Fatigue						
"Mental fatigue is characterized by the inability to maintain concentration and process information for decision-making efficiently after prolonged periods of cognitive activity." Does this statement describes mental fatigue as experienced in orienteering?	0%	5.3%	5.3%	42.1%	47.4%	Yes
Do you believe mental fatigue will occur in the following situation?						
- Insufficient recovery (i.e sleep deprivation, not taking breaks)	0%	0%	15.8%	15.8%	68.4%	Yes
- After a prolonged period of a cognitive task	0%	0%	5.3%	36.8%	57.9%	Yes
- After a prolonged period of a physical task	0%	10.5%	5.3%	63.2%	21.1%	Yes
- After repetitive task	0%	0%	42.1%	42.1%	15.8%	No
- After a task requiring high levels of concentration	0%	0%	0%	26.3%	73.7%	Yes
- Adapting to a new or unfamiliar situation?	5.3%	0%	10.5%	57.9%	26.3%	Yes
Are the following components affected by mental fatigue in daily life?						
- Level of concentration	0%	0%	0%	42.1%	57.9%	Yes
- Level of motivation	0%	0.0%	15.8%	31.6%	52.6%	Yes
- Emotional stability	0%	5.3%	10.5%	47.4%	36.8%	Yes
The Development of Mental Fatigue						
In orienteering training, is mental fatigue influenced by the following?						
- Complexity of the task	0%	0%	0%	47.4%	52.6%	Yes
- Lower level of fitness §§	0%	10.5%	36.8%	36.8%	15.8%	No
- Technically demanding training	0%	0%	5.3%	26.3%	68.4%	Yes
- Insufficient recovery	0%	0%	10.5%	26.3%	63.2%	Yes
- Non-orienteering challenges (e.g from work/ school)	0%	5.3%	0%	47.4%	47.4%	Yes
In orienteering competition, is mental fatigue influenced by the following?						
- Time of the competition §§	0%	21.1%	21.1%	26.3%	31.6%	No
- Environmental conditions §§	0%	5.3%	26.3%	42.1%	26.3%	No
- Physical condition	0%	10.5%	10.5%	63.2%	15.8%	Yes
- Mental condition	0%	0%	5.3%	31.6%	63.2%	Yes
- Prolonged racing schedule/season	0%	0%	5.3%	42.1%	52.6%	Yes
- Insufficient mental rest during competition	0%	0%	5.3%	47.4%	47.4%	Yes
Can the mental fatigue experienced in competition be replicated in training?**	0%	15.8%	15.8%	63.2%	5.3%	No

Table 4.3 Continued.

Statements	Totally disagree	Disagree	Neutral	Agree	Totally agree	Consensus
The Cause of Mental Fatigue						
Is the following orienteering technical task a cause of mental fatigue in orienteering?						
- Map reading (including map visualisation)	0%	0%	0%	52.6%	47.4%	Yes
- Navigation (react to surround environment/ features/ terrain)	0%	0%	10.5%	63.2%	26.3%	Yes
- Route choice selection	0%	5.3%	15.8%	42.1%	36.8%	Yes
Would intentionally increasing the volume of work on the following component induce mental fatigue in orienteering?						
- Map reading (including map visualisation)	0%	0%	0.0%	42.1%	57.9%	Yes
- Navigation (react to surround environment/ features/ terrain)	0%	0%	26.3%	26.3%	47.4%	Yes
- Route choice selection	0%	5.3%	15.8%	26.3%	52.6%	Yes
Is the following component the main cause of mental fatigue in orienteering competition?						
- Concentration level (amount of focus required for the task)	0%	0%	0%	31.6%	68.4%	Yes
- Repeated action	0%	11.1%	61.1%	22.2%	5.6%	No
- Complexity (difficulty of the task)	0%	0%	22.2%	33.3%	44.4%	Yes
- External pressures/ stress	5.6%	5.6%	11.1%	38.9%	38.9%	Yes
In orienteering competition, does that the following component act as an external stress that increases mental fatigue?						
- Fear of losing	0%	15.8%	31.6%	36.8%	15.8%	No
- Losing concentration	0%	5.3%	31.6%	47.4%	15.8%	No
- Losing attentional focus	0%	5.3%	21.1%	47.4%	26.3%	Yes
- Distraction (e.g. commentator/ other athletes)	0%	10.5%	21.1%	36.8%	31.6%	No
You can experience mental fatigue without being physically fatigued	0%	0%	0%	36.8%	63.2%	Yes
Mental fatigue is worse when you are physically fatigued	0%	0%	26.3%	36.8%	36.8%	Yes
The Impacts of Mental Fatigue						
Mental fatigue alters your pacing strategy by increasing your intention to walk and/or run slower than you expected during orienteering**	0%	26.3%	21.1%	47.4%	5.3%	No
Mental fatigue negatively affects your high-speed running performance during orienteering**	5.3%	15.8%	31.6%	36.8%	10.5%	No
In orienteering, the following psychological responses can occur when you are mentally fatigued.						
- Demotivated	0%	10.5%	5.3%	52.6%	31.6%	Yes
- Distraction §§	0%	5.3%	5.3%	26.3%	63.2%	Yes
- Stressed (e.g pressure from action and/or environment) §§	0%	10.5%	31.6%	21.1%	36.8%	No
- Confusion	5.3%	0%	5.3%	31.6%	57.9%	Yes
- Tension (e.g worried, nervous) §§	0%	10.5%	26.3%	52.6%	10.5%	No

Table 4.3 Continued.

Statements	Totally disagree	Disagree	Neutral	Agree	Totally agree	Consensus
- Fatigue (e.g worn out, exhausted, sleepy, tired)	0%	0%	0%	73.7%	26.3%	Yes
- Anger (e.g annoyed, bad tempered) §§	5.3%	10.5%	36.8%	42.1%	5.3%	No
You can experience mental fatigue in the following orienteering situation.						
- Long course with easy terrain	5.3%	15.8%	36.8%	42.1%	0%	No
- Short course with easy terrain	10.5%	36.8%	36.8%	15.8%	0%	No
- Long course with tricky terrain	0%	0%	5.3%	31.6%	63.2%	Yes
- Short course with tricky terrain	0%	5.3%	5.3%	36.8%	52.6%	Yes
- Easy route choice	10.5%	31.6%	47.4%	10.5%	0%	No
- Difficult route choice	0%	5.3%	5.3%	63.2%	26.3%	Yes
Pre-competition mental readiness affects the amount of mental fatigue experienced during orienteering	0%	0%	5.3%	52.6%	42.1%	Yes
The Methods to Reduce Mental Fatigue in Orienteering						
The following training methods are effective in reducing mental fatigue in orienteering:						
- Combined physical and orienteering technical training (i.e. running with map)	0%	0%	5.3%	42.1%	52.6%	Yes
- Physical training only (Improve physiological tolerance)**	5.3%	15.8%	36.8%	42.1%	0%	No
- Orienteering technical training only (i.e. improve the accuracy and efficiency of map reading skills and route choices)	0%	5.3%	10.5%	68.4%	15.8%	Yes
- Mental training (i.e. practice planning route and visualise the race using a map)	0%	5.3%	15.8%	52.6%	26.3%	Yes
The following training parameters need to be manipulated to induce mental fatigue:						
- Training intensity (e.g. prescribe a higher rating of perceived exertion (RPE) training session)	0%	15.8%	5.3%	47.4%	31.6%	Yes
- Training frequency (more training session)	0%	5.3%	26.3%	47.4%	21.1%	Yes
- The complexity of the training (i.e more advanced technique is needed to complete the task)	0%	0%	5.3%	26.3%	68.4%	Yes
- Training volume	0%	5.3%	42.1%	36.8%	15.8%	No
The following methods could reduce the amount of mental fatigue during orienteering:						
- Supplementation (e.g. energy gel, caffeine)	5.6%	11.1%	11.1%	72.2%	0%	Yes
- Mental breaks (i.e. mental rest between cognitively demanding activities)	0%	0%	5.3%	57.9%	36.8%	Yes
- Distraction (e.g. setting up a watch alarm)	5.3%	36.8%	36.8%	21.1%	0%	No

**: The items that failed to reach a consensus for two consecutive rounds; §§: No specific comments were received to revise the items.

Round 3

The expert panel were advised to give opinions regarding round two of the survey, which were then applied to the refinements of the survey questions for Round 3 of the survey. Four items were eliminated from further examination as there was no agreement in the first and second rounds, as presented in Table 4.3: one item about the development of mental fatigue in orienteering, two regarding the impacts of mental fatigue, and one about the methods to reduce mental fatigue in orienteering. Additionally, seven items were removed from further examination as the expert panel had not provided specific suggestions that could be used to revise the items, as indicated in Table 4.3: Lower level of fitness, Time of the competition, Environmental conditions, Distraction (e.g. commentator/ other athletes), Stressed (e.g. pressure from action and/ or environment), Tension (e.g. worried, nervous), and Anger (e.g. annoyed, bad-tempered). In addition, a consensus was reached in Round 2 that the complexity/difficulty of the task was the main source of mental fatigue in orienteering competitions. Thus, three items related to the complexity of the orienteering situation were removed in round 3 to avoid duplication and redundancy.

No further questions regarding the development, causes and impact of MF in orienteering were asked in Round 3, as an agreement was reached in either Round 1 or 2. Based on the responses of the orienteering experts in the second round, the remaining six items from five questions were revised. Although the panel had already agreed on the definition of MF in the first and second rounds, they still provided comments to further refine the statement. For the third round, 18 expert panel members completed the survey (94% response rate). Table 4.4 reveals that four out of six items achieved a consensus level of 70% or above.

To conclude, following three rounds of surveys over a three-month period, only 5 participants dropped out of the investigation. The study achieved a 100% completion rate in round 1, 79% in round 2, and 94% in round 3. Consequently, 79% of the originally recruited participants completed all three rounds of surveys.

Table 4.4 The descriptive summary of the responses from 18 orienteering experts who participated in the survey during the third round.

Statements	Totally disagree	Disagree	Neutral	Agree	Totally agree	Consensus
<u>The Definition of Mental Fatigue</u>						
"Mental fatigue is characterized by the inability to maintain concentration and process information for decision-making efficiently and effectively after a prolonged period of cognitively loaded activity." Do you agree this statement describe the mental fatigue you experienced in orienteering?	11.1%	0%	0%	44.4%	44.4%	Yes
Do you agree mental fatigue in daily life can occur when engaging the activity that you do not enjoy?	0%	16.7%	27.8%	33.3%	22.2%	No
<u>The Cause of Mental Fatigue</u>						
Do you agree a competitive environment is a cause of psychological stress that induces mental fatigue in orienteering?	5.6%	5.6%	11.1%	61.1%	16.7%	Yes
<u>The Methods to Reduce Mental Fatigue in Orienteering</u>						
Do you agree the higher perceived importance of orienteering competition affects the level of mental fatigue athletes experience during orienteering?	0%	16.7%	33.3%	22.2%	27.8%	No
Repeated high intensity and/ or high-quality orienteering technical training can help automating the actions in orienteering.	0%	0%	0%	27.8%	72.2%	Yes
Repeated high intensity and/ or high-quality orienteering technical training can improve the efficiency of decision-making during orienteering.	0%	0%	0%	22.2%	77.8%	Yes

4.4 Discussion

The Definition of Mental Fatigue

This study initially asked the expert panel to identify situations where they believed MF could occur in daily life. In accordance with existing definitions of MF (Habay et al., 2021; Pageaux et al., 2014; Van Cutsem et al., 2017), the expert panel agreed that MF arises after performing a prolonged cognitive task. The panel also concurred that MF can appear after a prolonged physical task and/or a task requiring a high level of concentration. This implies that if a task requires a high level of concentration and precision decision-making, it can lead to MF regardless of its duration. Functional magnetic resonance imaging studies have found that the fronto-parietal brain network presented negative changes, which are accompanied by higher MF ratings and slower reaction time after sustained attention tasks (Taya et al., 2018). However, the expert panel did not reach a consensus that MF is caused by repetitive tasks or activities which are not particularly enjoyable. This is consistent with the findings that the development of MF might be related to the amount of effort invested rather than the length and repetition of the activity (Giboin & Wolff, 2019). Two recent meta-analyses have revealed similar findings (Brown et al., 2020; Giboin & Wolff, 2019), suggesting that the level of MF is connected to the effort invested rather than the time spent on the task. Interestingly, the expert panel in round 2 were in agreement that MF is likely to occur when adapting to a new or unfamiliar environment and in the absence of recovery. Recent research involving elite netballers and football players suggests that the perceived MF remains higher than before training/competition during a netball training camp and following a soccer match (Abbott et al., 2020; Russell et al., 2021; Thompson et al., 2020). This supports the consensus of the expert panel that the cognitive and physical demand of the task, insufficient recovery as well as the unpredictability of the environment connected to the presence of MF.

The expert panel in round 1 agreed that the definition of MF in previous research adequately reflected its impact on physical performance (Pageaux et al., 2014; Van Cutsem et al., 2017). However, the expert panel expressed concerns that the existing definition did not fully correspond to the MF they experienced in orienteering. Taking into account the varying interpretations of MF in the literature (Brown et al., 2020; Martin et al., 2018; Tran et al., 2020), this study refines the definition of MF based on the recurrent comments from the expert panel from rounds 1 and 2. This feedback included but was not limited to "*mental fatigue in* *orienteering more as influencing the ability to concentrate and ability to make good decisions or effectively plan for the route or notice problems in time and act appropriately*" and "*leading to inefficient processing of thoughts and poor decision-making ability*". The expert panel achieved a consensus in round 3 that the revised definition accurately reflected the MF experienced in orienteering: *"Mental fatigue is characterized by the inability to maintain concentration and process information for decision-making efficiently and effectively after a prolonged period of cognitively loaded activity"*.

Summary: The expert panel involved in this study agreed with the existing definition of MF but suggested that incorporating elements related to decision-making and concentration might provide a more accurate representation of the MF they experienced during orienteering. Consequently, our findings suggest that the definition of MF commonly used in laboratory-based experiments may be inadequate to describe MF in orienteering. To effectively address MF in orienteering, our findings suggest that a specific operational definition of MF should be established to describe the phenomenon after a mentally demanding task. Furthermore, further research should explore other contributing factors, such as recovery, which may be related to MF and help refine the definition of MF in sports.

The Development of Mental Fatigue

The expert panel in round 1 agreed that MF exists in orienteering. However, they could not reach a consensus on whether the MF induced by an orienteering competition could be replicated in a training setting. The expert panel's responses suggested that the context of MF in a competition may differ from the training environment. In subsequent rounds 2 and 3, the panel ultimately agreed that the mental strain and pressure from adversaries were key stimuli for MF in orienteering competition, which cannot be duplicated in orienteering training. Consequently, it is advised that MF in orienteering be investigated and discussed separately for orienteering training and competition contexts.

In round two, the expert panel reached a consensus that the complexity of the task and the demands of technical training could be contributing factors to MF during orienteering training. This aligns with previous research (Giboin & Wolff, 2019; O'Keeffe, Hodder, & Lloyd, 2019; Van Cutsem et al., 2017) which has highlighted the significance of assessing the intensity of cognitive activity in understanding MF. O'Keeffe et al. (2019) highlighted the importance of a personalised approach to investigate MF, which could impact the extent to which MF can be induced realistically i.e. replicate the competition-induced MF during training. The expert panel in round 2 agreed that non-orienteering challenges from daily activities and inadequate recovery can affect the MF experienced during orienteering training. This supports previous findings that MF may accumulate over time or during intensive training if there is insufficient recovery. However, it was beyond the scope of this study to examine the particular types of non-orienteering tasks that contribute to the development of MF during both orienteering training and competition. Previous research has indicated that prolonged smartphone use can cause MF and negatively affect subsequent sports performance (Fortes et al., 2020; Fotes et al., 2021; Trecroci et al., 2020). Moreover, Martin et al. (2019) discovered that individuals regularly exposed to a highly cognitively demanding environment tend to be more resilient to MF, which supports the findings of Eccles et al. (2006a) that orienteers who compete regularly may be less vulnerable to MF. However, the expert panel did not reach a consensus on whether the fitness level of the orienteers could influence the magnitude of MF experienced during orienteering training. This indicates that the adaptation of cognitive training is more important than physical fitness in terms of coping with or reducing MF (Eccles, 2015).

The expert panel agreed that mental readiness for competition and/or a long racing schedule or season may have an impact on the development of MF in orienteering competitions. Similar to previous research conducted with elite athletes (Russell et al., 2019; Russell et al., 2021; Russell et al., 2022), our findings also support the explanation that MF can be caused by cumulative fatigue throughout the season. Specifically, the expert panel concluded that a lack of mental recovery during a single event combined with athletes’ physical condition, would affect the development of MF. This signifies that MF may increase both acutely and chronically in orienteering. However, the overall concentration and physical intensity needed during competition depend on how orienteers execute their tactical plan (Batista et al., 2020; Eccles et al., 2002). Therefore, orienteers can manage their physical output and allocate mental rest during orienteering competitions through self-regulated ability. However, if they become overloaded either cognitively or physically (or both), mistakes such as incorrect route choice and misinterpreting the map can occur, indicating that continuous decision-making during orienteering competition can directly affect the development of MF. As mentioned earlier, the replicability of competition-induced MF is low due to the difficulty in duplicating the stress and mental pressure elicited by other competitors. According to Phillips-Wren and Adya (2020), the presence of different stressors reduces the quality of decision-making. The expert panel agreed that psychological stressors could result in an increased number of errors, increasing both the physical and cognitive load of the task, thereby accelerating the development of MF. However, there was no consensus on how the time of the competition and environmental conditions would affect the degree of MF during orienteering competition. Previous research has suggested that experienced orienteers mentally prepare by visualizing the map and terrain before and during the competition (Eccles, 2006b; Eccles, 2008), which implies that environmental conditions may play a lesser role in contributing to MF. This suggests that the development of MF in orienteering may be largely driven by internal factors such as conscious decision-making and emotional state, combined with uncontrollable variables like a prolonged or condensed racing schedule. Based on our findings, it appears that MF during orienteering competition can have a detrimental effect on performance. Further research is necessary to understand the effects of a lengthy racing schedule, and inadequate mental breaks during competition to help orienteers and coaches develop strategies to effectively manage these issues.

The expert panel concluded that cognitive demand and emotional state are fundamental factors in the development of MF in orienteering training and competition. Future studies need to consider these components when analysing the elicitation of MF in orienteering. While there is a potential difference in MF between orienteering training and competition, the expert panel agreed that MF can develop over time. Furthermore, it was suggested that future studies should consider incorporating MF measurement into daily practice, as there is evidence that MF can develop chronically (Russell et al., 2022). To strengthen the argument, future research should measure other psychological responses such as perceived physical fatigue, perceived stress, and sleep quality, as reported by Russell et al. (2022), to explore whether MF can be elicited independently of other psychological responses. To date, no reliable and valid method is available to measure MF objectively due to technological limitations and methodological deficiencies reported in previous studies (Holgado et al., 2020; Martin et al., 2018; Smith et al., 2018; Van Cutsem et al., 2017). Therefore, future research should consider sport-specific variables that may contribute to MF. Instead of merely hypothesising about the efficacy of existing computerised MF protocol, the emotional state of the athletes should be considered when exploring the development of MF in orienteering training and competition.

Summary: The expert panel agreed that the MF experienced during an orienteering competition could not be replicated in training, due to the disparity in cognitive demands, mental state, and environmental conditions between training and competition. To ensure the validity of future studies, the expert panel recommended that further research into MF in orienteering should investigate competition and training separately.

The Causes of Mental Fatigue

There was consensus that multi-tasking in orienteering is cognitively challenging, with map reading, navigation, and route choice selection all contributing to MF. Remarkably, the expert panel agreed that deliberately increasing the workload of these components would increase MF in orienteering. Our findings suggested that cognitive effort is higher when activities are accompanied by a range of cognitive stresses, rather than a single stressor, which may not be sufficient to provoke MF. The protocols for inducing MF, such as the incongruent Stroop-colour task, should necessitate ongoing decision-making and the ability to suppress cognitive interference (Brown et al., 2020; Hotama et al., 2017; Van Cutsem et al., 2017). It appears that the key factor in inducing MF in orienteering is whether the task sufficiently challenges the orienteer's cognition. Given the limited evidence investigating the causes of MF, most research on MF has primarily relied on computerised cognitively demanding tasks, which often lack specificity and ecological validity (Brown et al., 2020; Habay et al., 2021; Smith et al., 2018; Van Cutsem et al., 2017). This study offers novel and potentially feasible causes of MF for future research, such as whether manipulating the amount of work of specified components can realistically induce MF in orienteering. It also suggests that future investigations into MF should consider using multiple cognitive stressors to effectively elicit MF.

The expert panel reached a consensus that the external pressures/stress (e.g. from other competitors), the complexity of the task, and the concentration level are the causes of MF during orienteering competition. Additionally, the expert panel agreed that a competitive environment and the loss of attentional focus are the potential causes of MF in competition. Although no consensus was reached on the influence of fear of losing, distraction, and losing concentration, it is clear that the competitive environment can serve as a source of external stress potentially triggering the development of MF. This is important because orienteers often have limited information about the map and terrain before the competition, highlighting the importance of competition-specific training to perform optimally (Eccles, 2008). The consensus of the expert panel highlights the essential role of attentional focus in orienteering competition, as orienteers must navigate unfamiliar terrain while attempting to complete the race as quickly as possible. The consensus obtained in this study reveals that different types of attentional focus may be responsible for the presence of MF, which requires further investigation. This consensus aligns with previous research in orienteering, which highlights that attentional focus is a fundamental element when exploring the cognitive demands placed on orienteers during competition (Celestino et al., 2015; Eccles, 2008; Eccles & Arsal, 2015; Eccles et al., 2002). Although the expert panel agreed that multi-tasking is cognitively challenging, they also noted that orienteers can overcome limitations in information processing through training adaption. Previous research has that the ability to control attentional focus is a key factor that differentiates the level of orienteers (Eccles et al., 2006a; Eccles, 2006b; Eccles et al., 2002). This provides additional evidence that orienteers strive to maintain a high degree of attentional focus to effectively execute their tactical plan, which could inadvertently lead to MF during competition.

The expert panel did not agree that MF and physical fatigue would increase simultaneously, demonstrating that orienteers can experience MF without being physically fatigued. However, the expert panel agreed that being physically fatigued could worsen MF during orienteering. Le Mansec et al. (2018) found that both MF and physical fatigue adversely affected sport-specific motor skills but further research is required to determine whether the degree of MF experienced is affected by physical fatigue. The expert panel supports the view that MF is distinct from physical fatigue, and future research should examine the causes of MF in orienteering.

Summary: The expert panel agreed that increasing the amount of work on map reading, navigation and route choice selection would lead to MF in orienteering. They also agreed that acute MF could be attributed to factors such as task complexity, concentration levels and external pressure or stress during orienteering competition. Additionally, the expert panel agreed that physical fatigue could accelerate the onset of MF; however, it is still possible to experience MF without being physically fatigued, demonstrating the need to investigate MF independently from physical fatigue.

The Impact of Mental Fatigue in Orienteering

In line with recent findings (Fortes et al., 2021; Habay et al., 2021; Trecroci et al., 2020), the expert panel agreed that MF impairs the capacity and precision of conscious decision-making in orienteering. The majority of responses related to the efficiency of route choice selection and map interpretation. Furthermore, the expert panel agreed that reaction time is affected by MF, which is a well-documented cognitive impairment under MF condition as discussed in section 2.5.1.1. While previous investigations have indicated that endurance running performance is negatively affected following cognitively demanding activities with individuals reporting a greater-than-normal perception of effort (Filipas et al., 2020; MacMahon et al., 2019; Van Cutsem et al., 2017), the expert panel did not agree that MF influences endurance or high-speed running performance in orienteering. Some conflicting views were expressed, such as: *"...MF can lead to a higher pace if panicking"* and *"...you will tend to slow down to make the navigation easier"*. This discrepancy may be related to the training status of the population as Martin et al. (2016) reported that professional endurance athletes are less vulnerable to MF, which supports the expert panel's opinion. Although the expert panel agreed that MF influences their ratings of perceived exertion and subjective ratings of tiredness, they believed that physiological variables are least affected by MF due to the minimal involvement of cognitive resources. Contrary to the majority of literature (Van Cutsem et al., 2017), the expert panel did not reach a consensus on the impact of MF on endurance performance. However, it is important to note that athletes and practitioners may have different perceptions and interpretations of the causes and effects of MF (Russell et al., 2019). MF comprises behavioural, subjective and physiological aspects, and all three do not need to be present for MF to be detected (Russell et al., 2019; Van Cutsem et al., 2017). This may explain why one can experience MF without exhibiting any cognitive impairment, due to the compensatory mechanisms in place. It is conceivable that this compensatory effect underlies the expert panel's agreement on the effects of MF on decision-making capacity and accuracy but not on high-speed and endurance running performance.

The expert panel agreed that orienteers may experience some negative psychological effects due to MF, including demotivation, confusion, fatigue and distraction, but not tension, anger or stress. Given that previous studies have adapted the BRUMS and the POMS to measure MF (Brown et al., 2020; Pageaux et al., 2014; Pires et al., 2018), the consensus from the expert panel supports the idea of assessing emotional state, as well as confusion. However, no consensus was reached regarding whether MF has a greater negative impact on emotional state than physiological capacity in orienteering. Importantly, previous research into elite athletes has revealed a carryover effect of MF that can sustain longer than a single occasion, particularly after a training camp or tournament (Abbott et al., 2020; Russell et al., 2021; Thompson et al., 2020). Performance may remain diminished and unable to return to pre-MF levels until the athlete has fully rested and recovered (Jacquet et al., 2021; Magnuson et al., 2021). Surprisingly, Abbott et al. (2020) discovered that MF can be more severe when athletes lose the match, suggesting that negative psychological responses and MF are closely linked. Consequently, it is possible that the effects of MF can impact performance on subsequent days. This may explain the expert panel's agreement that pre-competition mental readiness affects the degree of MF experienced during orienteering.

The findings of the expert panel suggested that the amount of MF would depend on the cognitive effort needed to complete the event. They were asked to determine when they expected to encounter the effects of MF in orienteering. They agreed that these effects would be greater in more complex and difficult terrain and routes, but less in simpler and easier ones. This consensus is in line with recent meta-analyses and systematic reviews (Brown et al., 2020; Giboin & Wolff, 2019), which have demonstrated that the amount of cognitive effort is closely linked to the presence of MF. This implies that the impact of MF in orienteering may be less dependent on the length of the task. Although the optimal duration to provoke MF remains unclear and not standardised (Habay et al., 2021; Van Cutsem et al., 2017), the current research provides novel evidence from international orienteering experts contributing to a deeper understanding of the development and impact of MF. Our findings suggest that when formulating an MF protocol to evaluate the impact of MF, attention should be given to the specific nature of the cognitive activities in the sport, instead of focusing on the duration of the task.

Summary: The expert panel concluded that the effects of MF in orienteering had a greater effect on cognitive variables such as decision-making, reaction time, subjective rating of tiredness and rating of perceived exertion than on running performance. The expert panel also agreed that MF can lead to a range of negative psychological changes, which impact the amount of MF experienced during orienteering.

The Methods to Reduce Mental Fatigue in Orienteering

The expert panel in round one agreed that a combination of physical and orienteering technical training, or technical training alone, could help delay the development of MF in orienteering. It was established that repetitive, high-intensity and high-quality technical training plays a vital role in reducing MF. The consensus partially aligns with Filipas et al. (2020), who demonstrated that four weeks of endurance training successfully improved MF tolerance in untrained individuals during a cycling time-trial performance following a 90-minute computerised cognitively demanding task. Although there were no significant changes in variables such as RPE and mental exertion ratings (Filipas et al., 2020), untrained individuals were able to generate higher power output for the same stated RPE after the MF protocol. This indicates that the training adaptation could improve MF tolerance, which supports the consensus made by the expert panel.

No consensus was reached in our study regarding whether the fitness status of orienteers or the implementation of physical training alone could successfully reduce MF in orienteering. Similarly, there was no agreement on whether the volume and frequency of training would optimise adaptation to counteract MF in orienteering. While enhancing the physical tolerance of the athletes may postpone the development of MF, it does not guarantee MF will not occur, which may explain why the expert panel did not agree that increasing physiological tolerance can reduce the likelihood of experiencing MF. This consensus aligns with previous research, which has shown that trained and elite athletes present better cognitive performance and skills than amateur athletes (Batista et al., 2020; Scharfen & Memmert, 2019). Therefore, it is not possible to completely exclude the possibility that the training status of the individuals may contribute to their resistance to MF. Martin et al. (2019) reported that individuals consistently exposed to a mentally demanding environment may be more resilient to MF. Consequently, this suggests that orienteering athletes regularly exposed to mentally demanding training may be able to adapt to stressful cognitive conditions, potentially decreasing the effects of MF in orienteering.

The expert panel agreed that taking mental breaks during orienteering could be effective in minimising MF. Based on the expert panel's responses, they suggested the following ways for incorporating mental breaks during orienteering, such as: *"allow small mental breaks during the competition e.g. during running on a part and then decide when to be on the map again"* and *"while running on a track give a rest to the brain until the next entrance in the forest"*. This consensus aligns with previous studies that have demonstrated that taking mental breaks can reduce perceived MF and improve cognitive function (Li et al., 2016; Lim & Kwok, 2016; Lim et al., 2013; Qi et al., 2020). Blasche et al. (2018) found that a 6-minute dynamic mental break, including light aerobic and stretching exercises, is more effective at reducing perceived fatigue than static mental breaks, with its positive effect lasting at least 20 minutes. Recent observational studies with elite athletes have found that MF can accumulate after competition or an intense training schedule, and it does not dissipate immediately after the task is completed (Abbott et al., 2020; Russell et al., 2019; Russell et al., 2021; Thompson et al., 2020). It is known that the acute effects of MF can negatively impact sporting performance (Giboin & Wolff, 2019; Habay et al., 2021; Van Cutsem et al., 2017). Loch et al. (2020) demonstrated that a 20-minute mental break involving mental imagery and breathing exercises in a static lying position could reduce the perception of MF and restore emotional levels following a 60-minute computerised MF protocol. This supports the consensus that taking a mental break between mentally demanding activities might assist in reducing the immediate and cumulative effects of competition and training-induced MF in orienteering. However, the expert panel did not agree that MF could be reduced through distraction during orienteering, indicating that a mental break should involve relaxation techniques rather than a distraction from the mentally demanding task. The practicality of using mental breaks to reduce MF during physical activity has yet to be identified. Future research should explore the effects of dynamic mental break interventions on perceived MF during orienteering, with interventions lasting from one to ten minutes as proposed in previous research (Li et al., 2016; Lim & Kwok, 2016; Lim et al., 2013). Further research should also examine how static mental breaks can minimise perceived MF over multiple days of racing and throughout the training season.

Summary: The expert panel agreed that adjusting the intensity and complexity of both technical and mental orienteering training would optimise training adaptation, thereby delaying the onset of perceived MF in orienteering. Furthermore, practitioners may consider introducing a mental break intervention to help reduce perceived MF during orienteering.

4.5 Conclusions

This Delphi study is the first to refine the definition of MF and explore its development in orienteering based on the consensus of international elite orienteering athletes and practitioners. This research supports that MF can develop both acutely and chronically, with potential differences in MF between orienteering competition and training. It suggests that creating occasion-specific contexts could increase the transferability of future investigations. While it is well-documented that MF negatively affects endurance running capacity, this study concluded that MF affects the cognitive functions and emotional states of orienteers rather than their running performance. Delaying the occurrence of MF in orienteering may be achieved by adjusting the volume, intensity, and complexity of orienteering-specific activities, such as map reading, navigation, and route choice selection. Additionally, future investigation on whether being physically fatigued increases the amount of MF experienced during orienteering would be beneficial. This study identified the perceived causes and effects of MF in orienteering, which can guide orienteering practitioners in creating ecologically valid research on MF in orienteering. This research underscores the importance of considering individual characteristics in future research in order to provide a comprehensive explanation of the causes and effects of MF in sports.

Chapter 5: Changes in Perceived Mental fatigue, Physical fatigue, and Mood State of National-level Orienteers During and After an Orienteering Competition

Some of the findings from this chapter were presented at the British Association of Sport and Exercise Sciences (BASES) Conference in 2022:

Changes in mental fatigue, physical fatigue and mood state during a two-day orienteering competition

Citation:

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https://doi.org/10.1080/02640414.2023.2273097

5.1 Introduction

Mental fatigue is defined as a psychobiological state that occurs following a prolonged period of cognitively demanding tasks, resulting in increased subjective tiredness and reduced endurance performance (Van Cutsem et al., 2017; Habay et al., 2021). However, Chapter 2 of this thesis critiques the adequacy of the existing MF definition in explaining the experience of MF in sports. To optimise the discussion of MF in orienteering, this study adopts the revised definition from Chapter 4, where MF is characterised by the inability to maintain concentration and process information for decision-making efficiently and effectively after a prolonged period of cognitively loaded activity.

In contrast to the conclusion of previous systematic reviews and meta-analyses (Giboin & Wolff, 2019; Habay et al., 2021; Van Cutsem et al., 2017), Chapter 4 of this thesis found that international orienteering experts agreed that MF exists in orienteering training and competition but disagreed on whether MF impairs either high-speed or endurance running performance. The conflict between the views of orienteering experts and the literature may be due to the potential differences in the perception and interpretation of MF between practitioners/athletes and researchers as highlighted in Russell et al. (2019). Additionally, individual characteristics should be taken into consideration because previous research has shown that well-trained athletes and those who frequently engage in highly cognitively demanding environments are less affected by MF (Martin et al., 2016; Martin et al., 2019). As discussed in the literature review of this thesis, the major limitations in many investigations on MF are the inconsistency in the definition, aggravating factors and measurements of MF. These challenges make it difficult to fully understand the nature and impact of MF in orienteering. Chapter 4 provides preliminary evidence to increase the ecological validity of MF investigation in orienteering by gathering expert consensus from international orienteering experts.

Mentally fatigued soccer players use environmental information less efficiently, positioning themselves sub-optimally on the pitch, which subsequently affects the execution of their tactical plan during soccer small-sided games (Coutinho et al., 2018). A systematic review also found that MF impairs decision-making, reaction time and accuracy in open-skill sports (Habay et al., 2021). Batista et al. (2021) was the only study to investigate MF in orienteering, showing that the MF elicited by performing a 30-minute cognitively demanding task resulted in a 2.4-

minute longer completion time in the subsequent 3.1km orienteering race. The increased completion time could be due to the nature of orienteering as it requires orienteers to gather as much information as possible from the surrounding environment to identify the most energy-cost-efficient and quickest route to each control point using a map and compass (Batista et al., 2020; Creagh & Reilly, 1997). In this sense, MF may affect spatial positioning, reaction time and decision-making accuracy of orienteers during both training and/or competition.

Since most MF induction methods used in previous research were not highly specific, as summarised in section 2.4.2.1, the MF protocol may not sufficiently challenge one's cognitive output (Martin et al., 2016; Martin et al., 2019). Consequently, conclusions drawn from laboratory-based experiments may have limited transferability to real-world sports contexts. Recent research has attempted to investigate whether participating in competition induces MF in elite football players (Abbott et al., 2020; Thompson et al., 2020) and netballers (Russell et al., 2021). This approach overcomes the limitation of relying on artificial MF induction methods to explain the MF in sports, as the international orienteering experts highlighted in Chapter 4, implying that MF experienced in competition cannot be replicated in training. The investigation on elite football players and elite netballers has also reported that MF elicited by competition remains elevated up to 48 hours after the competition (Abbott et al., 2020; Russell et al., 2019; Thompson et al., 2020). Considering that individual characteristics also play a vital role in the extent of MF experience in sports (Martin et al., 2016; Martin et al., 2019), the combined high cognitive and physical demands of orienteering make orienteers an ideal population for MF research. Although Batista et al. (2021) reported a slower completion time in orienteering races after completing a computerised MF protocol, the limitations identified in section 2.4.3 of this thesis suggest that further research is needed to justify whether MF exists during orienteering competitions. Therefore, the aim of this study was to examine changes in perceived MF and other psychological responses during an orienteering competition. To facilitate a thorough investigation in this observational study, no hypothesis was formulated.

Research Question: Does mental fatigue occur during orienteering competition?

5.2 Methodology

Experimental design

This study employed an observational study design with repeated measures to examine changes in perceived MF and other psychological responses among national-level orienteers during orienteering competitions. This study was approved by the University of Edinburgh, Moray House School of Education Ethics Committee (Ref: NLAM15042022). Before participation, written informed consent was obtained from all participants, and for participants under the age of 18, consent from their parents or guardians was also obtained.

Participants

Sixteen international orienteers (10 males, 6 females, 20.8 ± 4.9 years, 1.77 ± 0.1 m, 63.7 ± 8.0 kg, 11.6 ± 5.5 years of orienteering experience) from Australia (n = 1), Austria (n = 1), Estonia (n = 1), England (n = 4), France (n = 1), Scotland (n = 4), Sweden (n = 1) and Switzerland (n = 3) national teams participated. The inclusion criteria for this study are specified in section 3.2. According to the International Orienteering Federation's world ranking list on 1 November 2022 (http://ranking.orienteering.org/?ohow=F) and the participant classification framework in McKay et al. (2021), one participant was categorised as Tier 5 world-class orienteer, five orienteers were categorised as Tier 4 elite orienteers, and the remaining ten orienteers were classified as Tier 3 national-level orienteers. According to precision planning for a paired-sample design using the Exploratory Software for Confidence Intervals (Version 1)(Cumming, 2012), a sample size of 17 was necessary to achieve an average target margin of error of 0.4 for a confident interval when using $\rho = 0.70$. However, the obtained sample size in this study ensures a target margin of error of 0.42 for a 95% confidence interval.

Procedure

The recruitment method can be found in section 3.2.1. In this study, two types of races were documented: races for selection to international events (n = 8) and races for orienteering world ranking points (n = 8). This study recorded 43 races from eight separate orienteering competitions, with varying numbers of competition days (4-day: n = 4; 3-day: n = 5; 2-day: n = 5; 1-day: n = 2). Data was collected using a survey administrated and distributed via Qualtrics (Qualtrics XM Platform, USA). Participants were instructed to complete the survey within 30 minutes of waking up each day (PRE) and within 30 minutes after each competition day (POST) as identical to similar research (Russell et al., 2022). Additionally, participants were required to complete the survey on the first (24POST) and second days (48POST) following the final day of the orienteering competition, as previous research has found that MF remains elevated at least one day after the competition (Russell et al., 2019; Abbott et al., 2020; Thompson et al., 2020). Due to challenges related to standardising equipment in field-based investigations (Russell et al., 2022; Russell et al., 2021), participants used their own electronic devices to complete the survey.

Online Survey Design

The daily self-report measurements in this study were adapted from Russell et al. (2022). Six initial items regarding the demographic characteristics of the participants including age, gender, height, body mass, geographical location, and year of experience in competitive orienteering were collected in the first survey. The subsequent surveys consisted of 20 items and included:

- a closed-ended question "Did you compete an orienteering race just now?" and an open-ended question for the perceived cause of mental fatigue during the orienteering competition "What do you believe are the causes of mental fatigue during the orienteering race you completed just now?"
- six sliding scales (0-100) for self-reported ratings on perceived mental fatigue, motivation, sleep quality, physical fatigue (PF), stress and tiredness; and,
- twelve items from the vigour, fatigue and confusion subscales of the BRUMS using a 0-4 numeric scale.

Given that MF has been shown to impact sport-specific reaction time and decision-making accuracy in a previous systematic review (Habay et al., 2021), participants were also required to complete a 30-word congruent and incongruent Stroop-colour task after completing the slider scales and the BRUMS scale, similar to previous research examining executive function before and after MF intervention (Fortes et al., 2020; Fortes et al., 2021). All participants completed the entire experiment process once during a competition as a familiarization trial.

Self-report Measures

Perceived MF, motivation, sleep quality, PF, stress and tiredness were measured using a 100-mm VAS, with standardised questions and descriptors for each variable displayed in Table 3.1 in section 3.3.2.2. According to section 3.3.2.3, the vigour and fatigue subscale of the BRUMS were used to assess mood state and detect mood impairment under the MF state. The inclusion of the confusion subscale from the BRUMS in this study was based on findings from Chapter 4, wherein international orienteering experts emphasised the importance of measuring confusion during mentally fatigued states in both training and competition. Participants were required to respond to a 5-point Likert scale by answering the standardised question "How do you feel right now" for a total of 12 items from the vigour (BRUMSV), fatigue (BRUMSF) and confusion (BRUMSC) subscale of the BRUMS as identical to Brandt et al. (2016). The rating for each item ranged from 0 to 4 (0 = not at all, 1 = a little, 2 = moderately, 3 = quite a bit, 4 = extremely). The four relevant items from each subscale were summed up to obtain a total score between 0 and 16.

Congruent and incongruent Stroop task

According to section 3.3.2.1, the Stroop task was used as an objective measure of MF. The design and instruction of the congruent and incongruent Stroop task were almost identical to those used by Lopes et al. (2020). Participants were required to respond to the colour of four different words (red, blue, green and yellow), rather than the meaning of the words. Fifteen congruent and fifteen incongruent words were displayed randomly on the screen. The words remained visible until the participant's response was submitted. The response time and accuracy of the response were recorded. The tests were performed on the same self-selected electronic device that participants used to complete the survey during familiarization and experimental trials. Participants were instructed to complete the Stroop task in a perceived quiet environment and to respond as quickly as possible. The timing and the overview of the measurements are depicted in Figure 5.1.

Pre-competition	Post-competition	24POST	48POST
1. MF	1. MF	1. MF	1. MF
2. Motivation	2. Motivation	2. Motivation	2. Motivation
3. Sleep Quality	3. PF	3. Sleep Quality	3. Sleep Quality
4. PF	4. Stress	4. PF	4. PF
5. Stress	5. Tiredness	5. Stress	5. Stress
6. Tiredness	6. BRUMS	6. Tiredness	6. Tiredness
7. BRUMS	7. Perceived cause of MF	7. BRUMS	7. BRUMS
8. Stroop task	8. Stroop task	8. Stroop task	8. Stroop task

Figure 5.1 The schematic diagram of the experimental protocol.

Wearable heart rate and GPS technology

The physical demands of the orienteering competition were quantified using a self-selected smartwatch equipped with HR monitoring and GPS capabilities. The mean HR, total running distance and average running speed per kilometre were calculated using the data from the smartwatches. There was no standardisation of the model of smartwatches and HR monitors due to the geographical limitation of the researcher. However, participants were advised to select a smartwatch that was compatible with either Strava (Strava, USA) or Garmin Connect (Garmin Ltd, USA). A systematic review has summarised that most wrist-worn photoplethysmography devices have acceptable validity in measuring HR during physical activities, and the HR data can be used for population-based investigation (Zhang et al., 2020). Therefore, HR was recorded through either wrist or chest straps depending on the equipment accessibility of the participants. Participants were instructed to activate the devices at least 15 minutes before the competition and to use the same smartwatches in all data collection sessions to improve consistency.

Statistical analysis

All data are presented as mean ± SD unless specified. In addition to the statistical analysis presented in section 3.4.2 of this thesis, the following specific data analysis was conducted for this chapter. The magnitude of changes in paired comparisons for MF, motivation, sleep, PF, stress, tiredness, BRUMS, reaction time and response accuracy of the Stroop task, and physical demand of the orienteering competition were measured using ES together with 95%CI. The first part of the analysis aggregated all outcome variables before (PRE) and after (POST) the orienteering races to illustrate the overall changes. Subsequently, the second part of the analysis examined the pre- and post-specific type of orienteering race both pre and post, as well as the data following the specific orienteering race (MD+1). Furthermore, this chapter also analysed the changes in all outcome variables immediately after the participants' final competition, 24POST and 48POST. A descriptive statistic was used to present the physical demand of orienteering competition.

In the supplementary analysis, LMM were employed to explore individual differences and random effects across participants during the orienteering competition, as described in section 3.4.2. This analysis aimed to investigate changes in the ratings of perceived MF, motivation, PF, stress, tiredness, BRUMS, reaction time, and response accuracy on the Stroop task after accounting for individual random effects. Participants were included as random intercept factors, while gender, time of measurement, and race type were treated as fixed factors. The model selection criteria were discussed in section 3.4.2. The data presentation were identical to the earlier analysis, with the first part examining the pre- and post-orienteering competition phases, and the second part focusing on the recovery phase, specifically from immediately after the final competition to 48POST, as well as comparisons to the values recorded before the first orienteering competition. A Bonferroni post hoc test was applied when significance is reported. The alpha was set at 0.05.

5.3 Results

Pre and post orienteering competition (43 races)

A total of 43 races were documented from all participants. The mean changes in all outcome variables from pre- to post-orienteering competition are shown in Figure 5.2. There was a large increase in the subjective ratings of PF and a moderate increase in MF and BRUMS fatigue scores after the orienteering competition. The tiredness and BRUMS confusion ratings showed small increases following the competition. Ratings of motivation and stress and BRUMS vigour ratings showed a small decrement following orienteering. In addition, a trivial decrease was reported in reaction time and response accuracy of the Stroop task. Due to the limited sample sizes, the remaining two orienteering competition types, relay (n = 5) and KO-sprint (n = 3) were excluded for further analysis.

Variables	PRE	POST	Mean Difference [95%CI]	Effect size [95%CI]
Mental Fatigue	29.7 ± 20	49.5 ± 26.7	19.9 [12.5 , 27.2]	0.84 [0.49 , 1.19]
Motivation	85.6 ± 17.9	76.3 ± 21.8	−9.3 [-16.5 , -2]	−0.47 [-0.83 , -0.09]
Physical Fatigue	39.3 ± 23.1	67.4 ± 23.2	28.1 [20.8 , 35.4]	1.21 [0.81 , 1.61]
Stress	42.3 ± 20.4	35.8 ± 25	−6.6 [-13.9 , 0.7]	−0.29 [-0.6 , 0.03]
Tiredness	40.7 ± 20.2	53.9 ± 29.5	13.3 [4 , 22.5]	0.52 [0.15 , 0.9]
BRUMS Vigour	8.3 ± 3.5	7.5 ± 4.1	−0.8 [-2.1 , 0.5]	−0.21 [-0.54 , 0.13]
BRUMS Fatigue	5.9 ± 4	8.3 ± 4.2	2.5 [1.3 , 3.7]	0.61 [0.3 , 0.92]
BRUMS Confusion	1.1 ± 1.7	2.8 ± 3.7	1.7 [0.6 , 2.8]	0.58 [0.19 , 0.97]
Stroop task Reaction Time	1178.1 ± 320.6	1141.2 ± 335	−37 [-116.1 , 42.3]	−0.11 [-0.35 , 0.12]
Stroop task Response Accuracy	29.5 ± 0.9	29.5 ± 1.1	0 [-0.5 , 0.4]	−0.05 [-0.48 , 0.39]

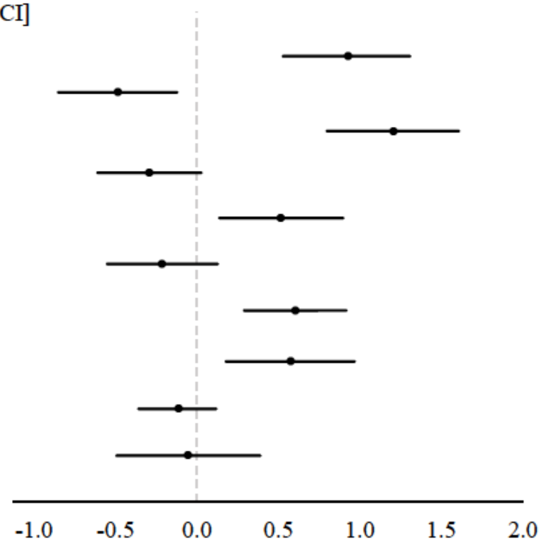


Figure 5.2 The magnitude of changes in all outcome variables pre and post-orienteering competition. Data has been combined from all participants (43 races).

Pre, post and 24-hour after sprint (12 races), middle-distance (13 races) and long-distance (10 races) orienteering competition

The mean change in all outcome variables before, immediately after, and 24 hours after (MD+1) sprint, middle-distance, and long-distance orienteering competitions are shown in Figure 5.3, with the magnitude of the changes presented in Table 5.1. The pre- to post-competition differences in the outcome variables were mostly consistent across the three events, except for ratings of tiredness, BRUMS vigour ratings, and Stroop task response accuracy in the sprint event, and reaction time during the Stroop task in the long-distance races. The extent of the changes varied in ratings of motivation, tiredness, BRUMSV, BRUMSF, and BRUMSC. Additionally, a moderate increase in tiredness ratings was found following middle- and long-distance competitions, with greater ratings observed in the long-distance race; no change was reported in the sprint event. There was a small to moderate extent of changes when comparing sprint to middle- and long-distance competition. While the BRUMSV scores trivially increased following the sprint event, a small to moderate decrease was reported following middle- and long-distance orienteering competitions. There was a small to moderate difference in the magnitude of change in BRUMSV ratings when comparing sprint to the other two race types as shown in Table 5.1. In terms of Stroop task response accuracy, a trivial to small decrease was observed in the middle- and long-distance competitions, whereas a small increase was found after the sprint event. The changes in response accuracy of the Stroop task in the middle-distance competition were moderately lower than in the sprint event. For the remaining outcome variables in Table 5.1, trivial to small magnitude of changes were found between different races. In summary, the long-distance competition demonstrated the greatest changes in subjective out measures except for motivation and MF ratings when compared to sprint and middle-distance competitions.

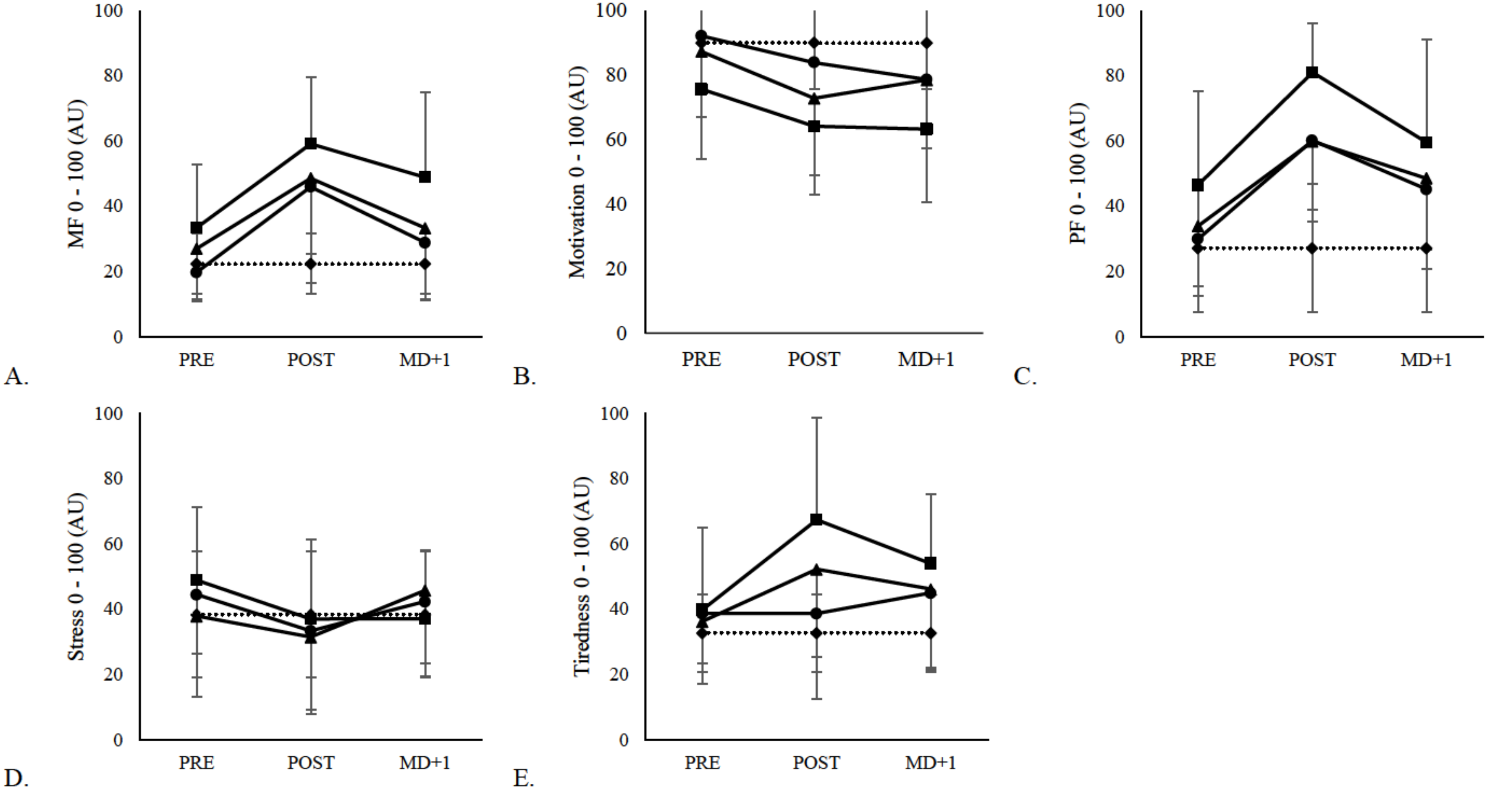


Figure 5.3 The changes in MF (A), motivation (B), PF (C), stress (D), tiredness (E), BRUMS - Vigour subscale (F), BRUMS - Fatigue subscale (G), BRUMS - Confusion subscale (H), Stroop task – Reaction time (I) and Stroop task – Response accuracy (J). The circle represents the ratings in sprint orienteering competition, triangle represents the middle-distance orienteering competition and the square represents the long-distance orienteering competition. The diamond dash line represents the mean value immediately before the first day of competition.

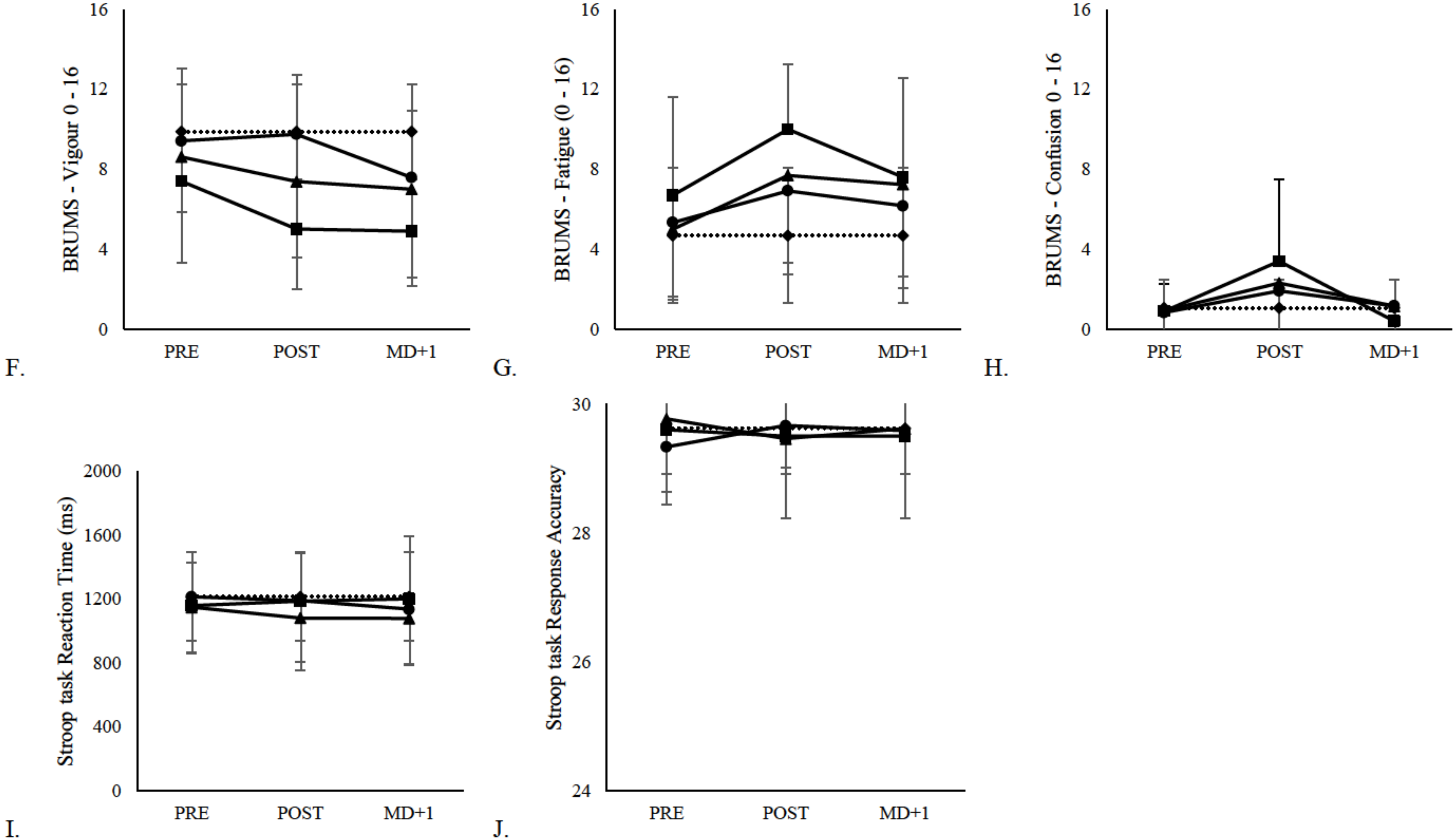


Figure 5.3 Continued.

Table 5.1 The changes in all outcome variables after sprint (n = 12), middle-distance (n = 13) and long distance (n = 10) orienteering competition.

Variables	PRE vs POST				POST vs MD+1			
	Mean difference [95%CI]	**Effect size [95%CI]**	**Changes between events (Effect size)**		**Mean difference [95%CI]**	**Effect size [95%CI]**	**Changes between events (Effect size)**	
			vs Middle	**vs Long**			**vs Middle**	**vs Long**
Mental Fatigue 0 – 100 AU								
Sprint	26.2 [10 , 42.4]	1.21 [0.36 , 2.02]	0.2 [-0.42 , 0.02]	-0.02 [-0.29 , 0.25]	-17.1 [-36.5 , 2.3]	-0.71 [-1.47 , 0.08]	0.07 [-0.14 , 0.29]	0.25 [-0.02 , 0.51]
Middle	21.5 [9.1 , 34]	1.09 [0.36 , 1.79]		0.2 [-0.06 , 0.47]	-15.3 [-25.3, -5.3]	-0.68 [-1.15 , -0.19]		0.24 [-0.02 , 0.51]
Long	25.7 [11.2 , 40.2]	1.28 [0.41 , 2.12]			-10.2 [-27.8 , 7.4]	-0.44 [-1.11 , 0.26]		
Motivation 0 – 100 AU								
Sprint	-8.3 [-17.6 , 1.1]	-0.58 [-1.19 , -0.06]	0.35 [-0.57 , -0.13]	-0.12 [-0.39 , 0.14]	-5.3 [-21.6 , 11.1]	-0.21 [-0.79 , 0.38]	0.49 [0.27 , 0.71]	0.16 [-0.1 , 0.43]
Middle	-14.5 [-26.7 , -2.2]	-0.66 [-1.21 , -0.08]		0.10 [-0.16 , 0.36]	5.6 [-5.5 , 16.7]	0.25 [-0.21 , 0.7]		-0.28 [-0.54 , -0.02]
Long	-11.5 [-36.7 , 13.6]	-0.54 [-1.57 , -0.52]			-0.9 [-20.7 , 18.9]	-0.04 [-0.82 , 0.74]		
Physical Fatigue 0 – 100 AU								
Sprint	30.3 [11 , 49.5]	1.42 [0.4 , 2.39]	-0.18 [-0.4 , 0.04]	0.15 [-0.11 , 0.42]	-15 [-29.7 , -0.3]	-0.69 [-1.34 , -0.01]	0.19 [-0.03 , 0.40]	-0.22 [-0.49 , 0.05]
Middle	25.9 [16.8 , 35]	1.31 [0.64 , 1.97]		0.41 [0.14 , 0.67]	-11.3 [-21.1 , -1.6]	-0.46 [-0.85 , -0.05]		-0.37 [-0.64 , -0.11]
Long	34.5 [16.1 , 52.9]	1.51 [0.51 , 2.46]			-21.5 [-46.5 , 3.5]	-0.87 [-1.81, 0.11]		
Stress 0 – 100 AU								
Sprint	-11.2 [-26.1 , 3.7]	-0.51 [-1.14 , 0.14]	0.21 [-0.01 , 0.43]	-0.04 [-0.3 , 0.23]	9 [-6.2 , 24.2]	0.37 [-0.22 , 0.95]	0.23 [0.02 , 0.45]	-0.37 [-0.63 , -0.1]
Middle	-6.4 [-20.1 , 7.4]	-0.27 [-0.8 , 0.27]		-0.29 [-0.55 , -0.02]	14.3 [1.5 , 27.1]	0.64 [0.05 , 1.21]		-0.62 [-0.88 , -0.35]
Long	-11.9 [-22.7 , -1.1]	-0.51 [-0.96 , -0.04]			0.1 [-17.6 , 17.8]	0 [-0.67 , 0.68]		

Table 5.1 Continued.

Variables	PRE vs POST				POST vs MD+1			
	Mean difference [95%CI]	Effect size [95%CI]	Changes between events (Effect size)		Mean difference [95%CI]	Effect size [95%CI]	Changes between events (Effect size)	
			vs Middle	vs Long			vs Middle	vs Long
Tiredness 0 – 100 AU								
Sprint	0 [-20.8 , 20.8]	0 [-0.87 , 0.87]	0.55 [0.33 , 0.77]	0.82 [0.54 , 1.09]	6.3 [-8 , 20.6]	0.26 [-0.27 , 0.77]	-0.51 [-0.73 , -0.29]	-0.88 [-1.16 , -0.61]
Middle	16 [0.8 , 31.2]	0.68 [0.03 , 1.32]		0.38 [0.12 , 0.64]	-6.1 [-21.7 , 9.5]	-0.24 [-0.79 , 0.32]		-0.31 [-0.57 , -0.04]
Long	27.6 [2.7 , 52.5]	0.97 [0.07 , 1.83]			-13.4 [-29.2 , 2.4]	-0.50 [-1.05 , 0.07]		
BRUMS Vigour 0 – 16								
Sprint	0.3 [-1.9 , 2.6]	0.1 [-0.51 , 0.7]	-0.4 [-0.62 , -0.18]	-0.73 [-1 , -0.46]	-2.2 [-3.7 , -0.6]	-0.68 [-1.18 , -0.16]	0.44 [0.22 , 0.66]	0.66 [0.39 , 0.94]
Middle	-1.2 [-3.8 , 1.3]	-0.37 [-1.08 , 0.35]		-0.28 [-0.55 , -0.02]	-0.4 [-3.5 , 2.7]	-0.09 [-0.77 , 0.59]		0.06 [-0.20 , 0.32]
Long	-2.4 [-5.2 , 0.4]	-0.67 [-1.41 , 0.09]			-0.1 [-2.7 , 2.5]	-0.04 [-0.84 , 0.77]		
BRUMS Fatigue 0 – 16								
Sprint	1.6 [-1.1 , 4.3]	0.4 [-0.24 , 1]	0.26 [0.04 , 0.48]	0.43 [0.16 , 0.7]	-0.8 [-2.6 , 1.1]	-0.18 [-0.59 , 0.23]	0.09 [-0.12 , 0.31]	-0.49 [-0.76 , -0.22]
Middle	2.7 [0.1 , 5.2]	0.69 [0.03 , 1.32]		0.15 [-.11 , 0.41]	-0.5 [-2.4 , 1.5]	-0.1 [-0.49 , 0.29]		-0.55 [-0.81 , -0.28]
Long	3.3 [0.6 , 6]	0.8 [0.11 , 1.45]			-2.4 [-5.1 , 0.3]	-0.57 [-1.18 , 0.06]		
BRUMS – Confusion 0 – 16								
Sprint	1.1 [-0.5 , 2.7]	0.46 [-0.17 , 1.07]	0.09 [-0.12 , 0.31]	0.48 [0.21 , 0.75]	-0.8 [-2.7 , 1.2]	-0.28 [-0.94 , 0.4]	-0.14 [-0.36 , 0.08]	-0.62 [-0.89 , -0.35]
Middle	1.4 [-0.9 , 3.7]	0.5 [-0.27 , 1.25]		0.31 [0.05 , 0.57]	-1.2 [-2.7 , 0.4]	-0.41 [-0.93 , 0.13]		-0.54 [-0.80 , -0.27]
Long	2.5 [0.1 , 4.9]	0.82 [0.02 , 1.59]			-3 [-5.9 , -0.1]	-1.02 [-1.98 , -0.02]		

Table 5.1 Continued.

Variables	PRE vs POST				POST vs MD+1			
	Mean difference [95%CI]	Effect size [95%CI]	Changes between events (Effect size)		Mean difference [95%CI]	Effect size [95%CI]	Changes between events (Effect size)	
			vs Middle	vs Long			vs Middle	vs Long
Stroop task Reaction Time (ms)								
Sprint	-24.5 [-230.1 , 181]	-0.06 [-0.52 , 0.4]	0.16 [-0.07 , 0.39]	-0.18 [-0.42 , 0.06]	-76.9 [-208.8 , 54.9]	-0.22 [-0.57 , 0.13]	0.03 [-0.19 , 0.25]	0.55 [0.28 , 0.82]
Middle	-67.3 [-187.8 , 53.1]	-0.24 [-0.63 , 0.16]		-0.41 [-0.64 , -0.18]	-70.3 [-193.4 , 52.9]	-0.25 [-0.64 , 0.16]		0.53 [0.26 , 0.79]
Long	28.3 [-160.7 , 217.3]	0.1 [-0.48 , 0.67]			42.5 [-118.3 , 203.3]	0.13 [-0.3 , 0.54]		
Stroop task Response Accuracy								
Sprint	0.3 [-0.3 , 1]	0.43 [-0.32 , 1.16]	0.73 [0.5 , 0.97]	0.31 [0.06 , 0.55]	0.3 [-0.3 , 0.8]	0.32 [-0.33 , 0.95]	-0.48 [-0.71 , -0.26]	-0.48 [-0.75 , -0.21]
Middle	-0.3 [-0.8 , 0.1]	-0.41 [-1 , 0.17]		-0.16 [-0.38 , 0.07]	-0.2 [-0.6 , 0.3]	-0.22 [-0.86 , 0.42]		0.08 [-0.18 , 0.34]
Long	-0.1 [-1.3 , 1.1]	-0.09 [-1.04 , 0.87]			-0.1 [-0.5 , 0.3]	-0.09 [-0.4 , 0.23]		

The comparison between post-competition and MD+1 showed similar directions of change in most outcome variables except for the reaction time of the Stroop task in long-distance, the response accuracy of the Stroop task and the ratings of tiredness in the sprint event, and motivation in middle-distance as shown in Figure 5.3 and Table 5.1. For the remaining outcome variables, the direction of change from post-competition to MD+1 was consistent, with declines in the ratings of MF, PF, BRUMSV, BRUMSF and BRUMSC.

Compared to pre-competition values, the ratings of MF, PF, stress, tiredness, BRUMSF and BRUMSC were higher, and motivation and BRUMS vigour were lower at MD+1 except for the ratings of stress in middle-distance competition and BRUMSC ratings in long-distance competition, as shown in Figure 5.3. The stress ratings after middle-distance competition remained higher than pre-competition values with a small ES (ES = 0.34 [-0.21 , 0.87]), and displayed a small to moderate difference in comparison to the changes in the sprint (ES = 0.52 [0.3 , 0.74]) and long-distance competitions (ES = -0.76 [-1.03 , -0.49]). The BRUMSC ratings in the long-distance competition were lower than pre-competition (ES = -0.46 [-1.48 , 0.59]), with a small difference compared to the changes in the sprint (ES = -0.4 [-0.67 , -0.13]) and middle-distance competition (ES = -0.42 [-0.68 , -0.15]) in MD+1.

When assessing the magnitude of changes between sprint and middle-distance competition in PRE vs MD+1, a trivial difference was observed for MF (ES = -0.18 [-0.4 , 0.04]), motivation (ES = 0.19 [-0.02 , 0.41]), PF (ES = -0.03 [-0.25 , 0.19], tiredness (ES = 0.14 [-0.08 , 0.36]), BRUMSV (ES = 0.06 [-0.16 , 0.28]) and BRUMSC (ES = -0.05 [-0.27 , 0.17]), while a small difference was reported in BRUMSF (ES = 0.37 [0.15 , 0.59]). When comparing sprint and long-distance competitions, small differences were reported in MF (ES = 0.41 [0.14 , 0.68]), and tiredness (ES = 0.29 [0.03 , 0.56]). Moreover, there was a trivial difference in the ratings of motivation (ES = -0.17 [-0.43 , 0.09]), PF (ES = -0.08 [-0.34 , 0.18]), tiredness (ES = 0.17 [-0.09 , 0.43]), and a small difference in MF (ES = 0.55 [0.29 , 0.82]), BRUMSV (ES = -0.21 [-0.47 , 0.06]) and BRUMSF (ES = -0.34 [-0.60 , -0.08]) in comparison to the magnitude of changes between middle- and long-distance competition.

Regarding the Stoop task, a small decrease in reaction time in PRE vs MD+1 was found in the sprint (ES = -0.22 [-0.57 , 0.13]) and middle-distance race (ES = -0.25 [-0.64 , 0.16]) but a trivial increase in long-distance race (ES = 0.13 [-0.3 , 0.54]). When comparing the extent of changes in the reaction time of the Stroop task in PRE vs MD+1, a trivial difference was found between sprint and middle-distance race (ES = -0.03 [-0.25 , 0.19]), but a small difference was reported between sprint and long-distance (ES = -0.55 [-0.82 , -0.28]), and middle- and long-distance race (ES = -0.53 [-0.79 , -0.26]). For the Stroop task response accuracy, the sprint races showed a small increase (ES = 0.32 [-0.33 , 0.95]), while the middle- (ES = -0.22 [-0.86 , 0.42]) and long-distance (ES = -0.09 [-0.4 , 0.23]) races reported trivial to small declines. Although there was a trivial difference (ES = -0.08 [-0.34 , 0.18]) between middle- and long-distance races, the sprint race showed a small difference in the magnitude of changes compared to middle- (ES = 0.48 [0.26 , 0.71]) and long-distance races (ES = 0.48 [0.21 , 0.75]).

Immediately post-24-hours and 48-hours post the final competition (n = 16)

Figure 5.4 displays the data for all outcome variables for each participant's final competition immediately after (POST), 24 hours after (24POST), and 48 hours after (48POST). The magnitude of changes in the outcome variables is in Table 5.2.

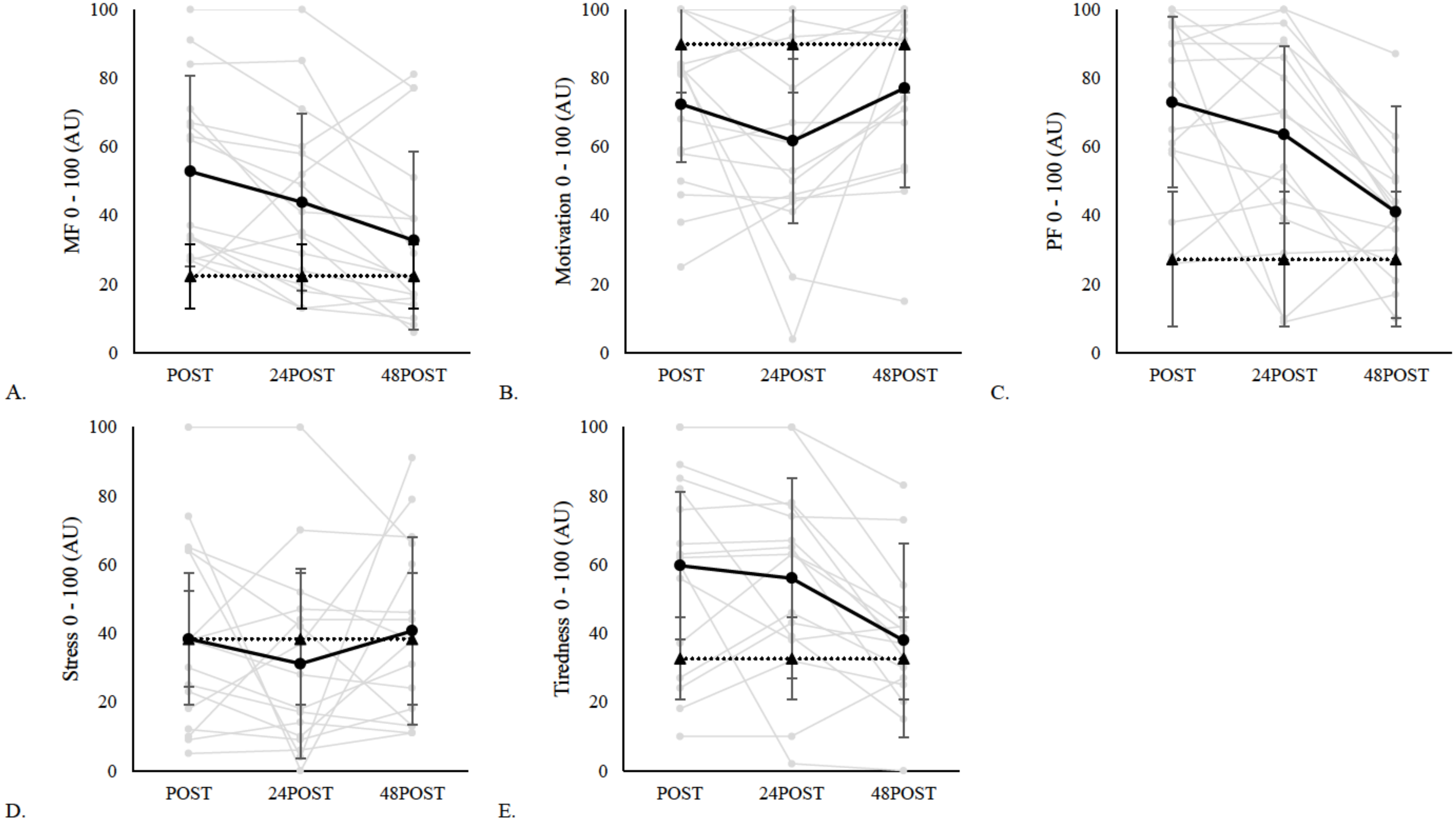
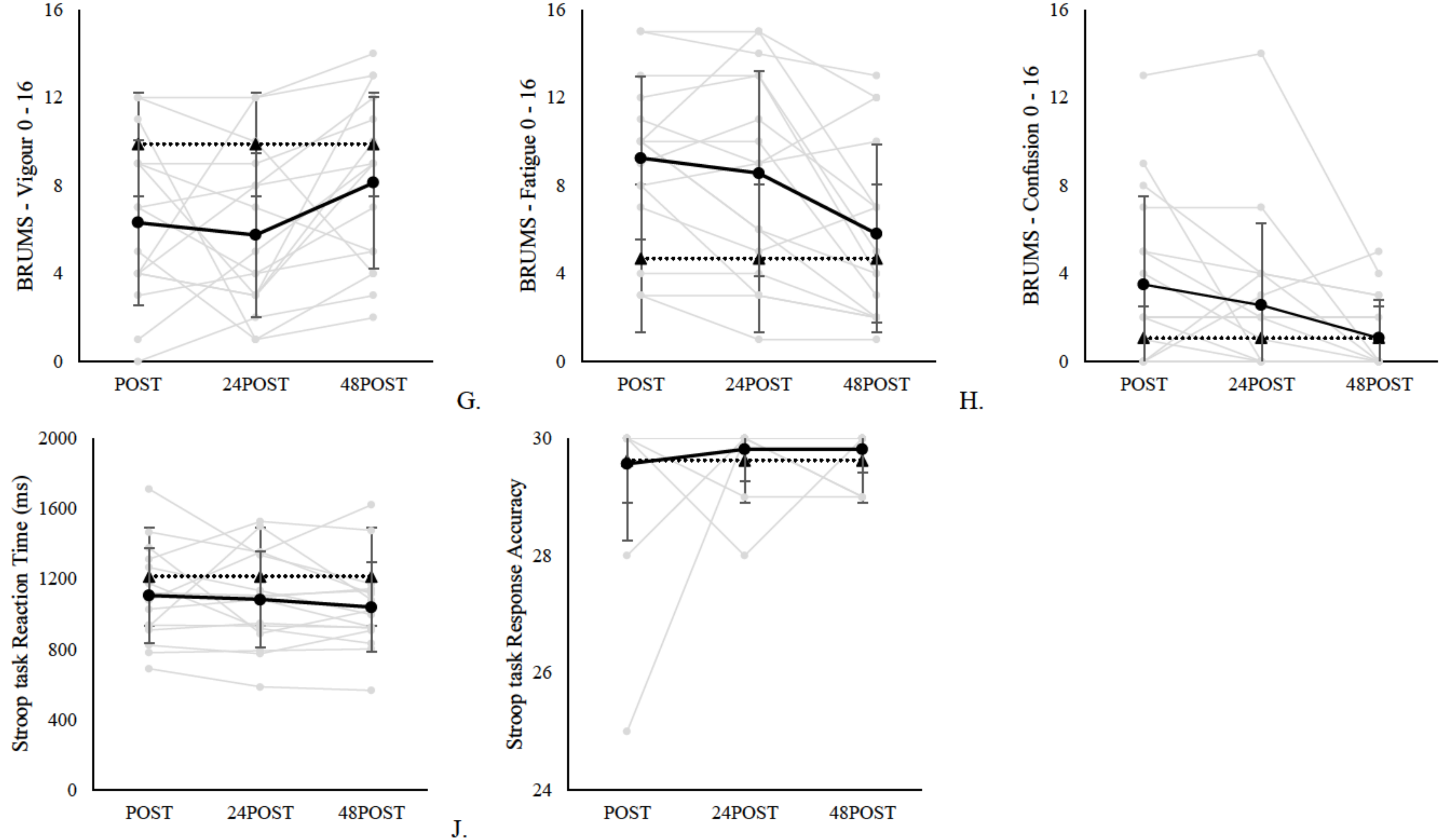


Figure 5.4 The changes in MF (A), motivation (B), PF (C), stress (D), tiredness (E), BRUMS - Vigour subscale (F), BRUMS - Fatigue subscale (G), BRUMS - Confusion subscale (H), Stroop task – Reaction time (I) and Stroop task – Response accuracy (J). The triangle dash line represents the mean value immediately before the first day of competition and the grey lines represent the individual ratings.



F. G. H. I. J.

Figure 5.4 Continued.

Table 5.2 The magnitude of the changes in outcome variables for immediately after the last day of the competition, 24hours- and 48-hours after the competition (n = 16).

Variables	POST vs 24POST		24POST vs 48POST	
	Mean difference [95%CI]	Effect size [95%CI]	Mean difference [95%CI]	Effect size [95%CI]
100-mm visual analogue scale				
MF	-8.9 [-17.1 , -0.8]	-0.35 [-0.66 , -0.03]	-11.1 [-21.6 , -0.7]	-0.43 [-0.83 , -0.02]
Motivation	-10.6 [-25 , 3.7]	-0.4 [-0.91 , 0.12]	15.4 [2.4 , 28.4]	0.57 [0.08 , 1.05]
PF	-9.4 [-25.2 , 6.5]	-0.33 [-0.85 , 0.2]	-22.6 [-34.5 , -10.7]	-0.88 [-1.4 , -0.34]
Stress	-7.2 [-22.3 , 7.9]	-0.26 [-0.77 , 0.26]	9.6 [-7.2 , 26.3]	0.36 [-0.24 , 0.95]
Tiredness	-3.6 [-15.3 , 8]	-0.13 [-0.5 , 0.25]	-18.1 [-28 , -8.2]	-0.74 [-1.18 , -0.27]
The Brunel Mood Scale 0 -16				
Vigour	-0.6 [-2.8 , 1.7]	-0.15 [-0.71 , 0.41]	2.4 [0.4 , 4.3]	0.62 [0.1 , 1.13]
Fatigue	-0.7 [-2 , 0.6]	-0.16 [-0.46 , 0.14]	-2.8 [-4.7 , -0.79]	-0.63 [-1.09 , -0.15]
Confusion	-0.9 [-2.5 , 0.6]	-0.24 [-0.63 , 0.15]	-1.5 [-3.1 , 0.1]	-0.52 [-1.06 , 0.04]
Stroop task performance				
Reaction time (ms)	-23.2 [-155.6 , 109.2]	-0.09 [-0.53 , 0.37]	-43.1 [-129.5 , 43.4]	-0.16 [-0.47 , 0.15]
Response accuracy	0.3 [-0.5 , 1]	0.25 [-0.48 , 0.97]	0 [-0.3 , 0.3]	0 [-0.65 , 0.65]

All outcome variables presented a decline from immediate post-final competition to 24POST, except for Stroop task response accuracy, which demonstrated a small increase. Specifically, there was a trivial decrease in the ratings of tiredness, BRUMSV and BRUMSF, while a small decrease in the ratings of MF, motivation, PF, stress and BRUMSC at 24POST. From 24POST to 48POST, there was a small decline in the ratings of MF, BRUMSC and the reaction time of the Stroop task, whereas the ratings of PF, tiredness and BRUMSF reported moderate decreases. In contrast, there was a small increase in stress ratings and a moderate increase in BRUMSV. Despite the small increase in Stroop task response accuracy at 24POST, no further changes were observed at 48POST. In comparison to before the first day of competition, the ratings of MF (ES = 0.54 [0.08 to 1.15], mean difference: 10.4 [-1.8 to 22.7]), PF (ES = 0.72 [-0.01 to 1.41], mean difference: 13.8 [-0.1 to 27.7]), stress (ES = 0.1 [-0.49 to 0.7], mean difference: 2.4 [-12.3 to 17]), tiredness (ES = 0.31 [-0.39 to 1.01], mean difference: 5.3 [-7.3 to 17.8]), BRUMSF (ES = 0.3 [-0.03 to 0.63], mean difference: 1.1 [-0.1 to 2.4]) and the response accuracy during Stroop task (ES = 0.32 [-0.25 , 0.88] mean difference: 0.2 [-0.2 , 0.5]) remained higher, while the ratings of motivation (ES = -0.63 [-1.3 to 0.06], mean difference: -12.8 [-27 to 1.5]), BRUMSV (ES = -0.54 [-1.05 to -0.02], mean difference: -1.8 [-3.4 to -0.1]) and the reaction time during Stroop task (ES = -0.66 [-1.09 to -0.21], mean difference: -174.9 [-28.4 , -65.7] remained lower than the pre-competition level at 48POST. However, at 48POST, BRUMSC returns to a level similar to pre-competition (ES = 0 [-0.6 to 0.6], mean difference: 0 [-1 to 1]). It is crucial to acknowledge the fluctuation in self-report ratings across individuals, with some individual ratings falling outside the standard deviation from the mean value. This is reflected in the wide 95%CIs in ES, as displayed in Figure 5.4 and Table 5.2, indicating a high individual variability in self-report ratings.

Perceived causes of mental fatigue during orienteering competition

Based on the summary of 41 responses recorded after the completion of each orienteering competition, eight perceived causes of MF were identified. The most frequently mentioned cause of MF during the orienteering competition was the physical demands of the race (56.1%). Around one-third of responses highlighted the stress from the race and/or mistakes (31.7%), the technical demand and/or the difficulty of the race (29.3%) and weather conditions i.e. heat or cold (26.8%). The remaining causes included the amount of concentration required for the race (24.4%), physical readiness for the race (17.1%), non-orienteering challenges e.g. travel or school (12.2%), and multiple race schedule (12.2%).

Physical demand of the orienteering competition (n = 13)

The GPS and HR data were collected from thirteen participants during orienteering races; however, HR data from three participants were unavailable because of technical issues. Table 5.3 illustrates the physical demands of the orienteering races. A moderate to large difference in the pace per kilometre was reported when comparing the sprint races to the middle-distance and long-distance events. Conversely, there was a small difference in the pace per kilometre between the middle- and long-distance races.

Table 5.3 The physical demand of different orienteering competition from 13 orienteers.

Type of competition (number of races)	Distance Covered (km)	Climb (m)	Completion time (hr:min:s)	Average speed (km/h)	Time taken per kilometre (min:s.ms)	Difference in distance covered/ time taken per kilometre Effect size [95%CI]		Mean HR* (bpm)
						vs Middle	vs Long	
Sprint (12)	3.54 ± 0.43	42.5 ± 22.51	0:17:19 ± 0:04:13	12.72 ± 2.41	04:53.3 ± 01:11.3	1.06 [0.77 , 1.34]	1.28 [0.85 , 1.72]	171 ± 12
Middle (10)	5.26 ± 1.29	102.8 ± 23.47	0:33:04 ± 0:07:34	9.79 ± 2.25	06:17 ± 01:26.3		0.25 [-0.17 , 0.66]	171 ± 10
Long (6)	12.83 ± 2.91	310 ± 86.75	1:25:21 ± 0:19:45	9.04 ± 0.98	06:39.1 ± 01:32.4			169 ± 15

*Result were calculated using 10 orienteer's heart rate data (Sprint: n = 10; Middle: n = 9; Long: n = 5).

Supplementary analysis addressing individual random effects

For the analysis of model fit before and after the orienteering competition, we compared models with and without random intercepts for participants (ID) across all outcome variables. For most outcome variables, the inclusion of a random intercept significantly improved model fit, including MF ($\chi^2(1) = 27.674$, $p < 0.001$), motivation ($\chi^2(1) = 22.74$, $p < 0.001$), PF ($\chi^2(1) = 30.28$, $p < 0.001$), stress ($\chi^2(1) = 28.85$, $p < 0.001$), tiredness ($\chi^2(1) = 21.65$, $p < 0.001$), BRUMSV ($\chi^2(1) = 9.33$, $p = 0.002$), BRUMSF ($\chi^2(1) = 32.03$, $p < 0.001$), BRUMSC ($\chi^2(1) = 5.13$, $p = 0.024$), and the reaction time of Stroop task ($\chi^2(1) = 104.92$, $p < 0.001$). These findings demonstrate noticeable individual variability in baseline scores for these variables, suggesting that random intercepts should be included in the models to account for this variability. However, the inclusion of a random intercept did not significantly improve model fit ($\chi^2(1) = 1$, $p = 0.319$) for the response accuracy of the Stroop task, indicating that individual variability in baseline Stroop task response accuracy is minimal and does not require adjustment for random intercepts. Due to variability in competition days and race order among individuals, the random slope model including race type was excluded from analysis due to convergence issues. To improve model stability, the analysis focused on the effects of time and gender for pre- and post-orienteering competition comparisons and the model comparisons are presented in Table 5.4.

Table 5.4 The model comparison between random intercept model and random intercept plus random slopes model for pre- and post-orienteering competition.

Variable	Model	AIC	BIC	Log-likelihood	χ^2	df	p
MF	Random Intercept (Participant ID)	774.61	786.88	-382.31	-	-	-
	Random Slope: Participant x Gender	778.02	795.20	-382.01	0.59	2	0.745
	Random Slope: Participant x Time	772.81	789.99	-379.4	5.21	0	< 0.05
	Random Slopes: Participant x Gender x Time	777.28	801.82	-378.64	1.53	3	0.675
Motivation	Random Intercept (Participant ID)	754.51	766.78	-372.26	-	-	-
	Random Slope: Participant x Gender	758.46	775.64	-372.23	0.05	2	0.975
	Random Slope: Participant x Time	757.94	775.12	-371.97	0.52	0	N/A
	Random Slopes: Participant x Gender x Time	763.29	787.84	-371.65	0.65	3	0.885
PF	Random Intercept (Participant ID)	766.29	778.56	-378.15	-	-	-
	Random Slope: Participant x Gender	767.16	784.34	-376.58	3.13	2	0.209
	Random Slope: Participant x Time	770.19	787.37	-378.10	0	0	N/A
	Random Slopes: Participant x Gender x Time	773.06	797.60	-376.53	3.13	3	0.372
Stress	Random Intercept (Participant ID)	772.93	785.20	-381.47	-	-	-
	Random Slope: Participant x Gender	776.85	794.03	-381.42	0.09	2	0.958
	Random Slope: Participant x Time	776.89	794.07	-381.45	0	0	N/A
	Random Slopes: Participant x Gender x Time	781.94	806.48	-380.97	0.96	3	0.812
Tiredness	Random Intercept (Participant ID)	792.56	804.83	-391.28	-	-	-
	Random Slope: Participant x Gender	796.55	813.73	-391.27	0.01	2	0.994
	Random Slope: Participant x Time	790.97	808.15	-388.48	5.58	0	N/A
	Random Slopes: Participant x Gender x Time	796.91	821.45	-388.45	0.06	3	0.996
BRUMSV	Random Intercept (Participant ID)	469.58	481.85	-229.79	-	-	-
	Random Slope: Participant x Gender	473.49	490.68	-229.75	0.09	2	0.958
	Random Slope: Participant x Time	472.91	490.09	-229.46	0.58	0	N/A
	Random Slopes: Participant x Gender x Time	477.92	502.47	-228.96	0.99	3	0.804
BRUMSF	Random Intercept (Participant ID)	459.89	472.16	-224.94	-	-	-
	Random Slope: Participant x Gender	462.91	480.09	-224.46	0.98	2	0.614
	Random Slope: Participant x Time	462.32	479.50	-224.16	0.59	0	N/A
	Random Slopes: Participant x Gender x Time	467.38	491.92	-223.69	0.94	3	0.815
BRUMSC	Random Intercept (Participant ID)	423.79	436.06	-206.89	-	-	-
	Random Slope: Participant x Gender	424.40	441.58	-205.20	3.39	2	0.184
	Random Slope: Participant x Time	414.18	431.36	-200.09	10.21	0	N/A
	Random Slopes: Participant x Gender x Time	419.41	443.95	-199.71	0.77	3	0.858

Stroop task reaction time	Random Intercept (Participant ID)	1173.8	1186.0	-581.89	-	-	-
	Random Slope: Participant x Gender	1176.1	1193.3	-581.06	1.65	2	0.439
	Random Slope: Participant x Time	1177.7	1194.9	-581.84	0	0	N/A
	Random Slopes: Participant x Gender x Time	1181.7	1206.3	-580.86	1.97	3	0.579

AIC: Akaike Information Criterion; BIC: Bayesian Information Criterion; χ^2: Chi-square.

Due to variability in competition days and race order among individuals, the random slope model including race type was excluded from the analysis because of convergence issues. To enhance model stability, the analysis focused on the effects of time and gender in pre- and post-orienteering competition comparisons, with model comparisons presented in Table 5.4. The results indicate that the random intercept model was the best fit for the ratings of motivation, PF, stress, tiredness, BRUMSV, BRUMSF, BRUMSC, and the reaction time of the Stroop task. Although the ratings of MF demonstrated a significant improvement in model fit when adding a random slope for Time, the absence of degree of freedom (df = 0) and p-value shows the result of convergence issue making it unable to estimate the random effects properly (Table 5.4). This suggests the model is too complex for analysis. Therefore, the ratings of MF also utilised the random intercept model for further analysis. Similarly, the convergence issues were also observed in the random intercept plus time random slope model in other variables, suggesting that these models were overfitting the data and could not generate reliable results. Additionally, the random intercept estimates for each individual of all outcome variables except the Stroop task response accuracy are presented in Table 5.5 The result reflects observable individual variability across participants. For example, in the ratings of MF, estimates range from -12.86 to 22.52, indicating a discrepancy in the baseline scores between individuals. Similar observations were also found in the ratings of motivation, PF, stress, tiredness, and BRUMSV. The observed individual differences suggest that accounting for individual variability with random intercepts is crucial for modelling the data accurately.

Table 5.5 The random intercepts estimate of each participant based on pre and post orienteering competition Linear Mixed Model.

Variable	ID	Random intercept estimate	Variable	ID	Random intercept estimate
MF	1	-5.82	Motivation	1	0.47
	2	-6.49		2	9.84
	3	0.19		3	-7.39
	4	-8.16		4	3.49
	5	-12.86		5	4.38
	6	-11.66		6	7.69
	7	3.78		7	0.12
	8	-6.45		8	-11.32
	9	14.29		9	-6.89
	10	-15.62		10	0.42
	11	9.16		11	-16.4
	12	6.56		12	-9.11
	13	22.52		13	6.96
	14	1.89		14	1.41
	15	11.74		15	4.07
	16	-2.58		16	12.26

PF	1	-6.51	Stress	1	13.71
	2	-10.9		2	-18.49
	3	2.09		3	-3.19
	4	-7.74		4	3.92
	5	-17.54		5	-14.41
	6	10.97		6	-14.09
	7	5.67		7	1.67
	8	-20.19		8	5.12
	9	0.12		9	3.03
	10	-3.91		10	-16.92
	11	10.38		11	17.6
	12	-2.26		12	-3.02
	13	18.58		13	21.2
	14	10.43		14	5.2
	15	13.91		15	-5.81
	16	-3.11		16	4.48
Tiredness	1	0.31	BRUMSV	1	1.61
	2	-13.44		2	0.86
	3	4.99		3	-0.78
	4	-12.58		4	0.86
	5	-5.8		5	0.5
	6	4.56		6	-0.26
	7	5.06		7	0.74
	8	-13.79		8	0.55
	9	5.17		9	-1.49
	10	-13.49		10	-0.18
	11	12.24		11	-1.29
	12	-3.19		12	0.65
	13	13.04		13	-2.27
	14	5.17		14	0.83
	15	6.1		15	-1.79
	16	5.65		16	1.47
BRUMSF	1	-1.32	BRUMSC	1	-0.46
	2	-3.29		2	-0.57
	3	0.65		3	-0.13
	4	-3.09		4	0.87
	5	-0.44		5	-0.82
	6	-0.04		6	0.47
	7	0.7		7	0.77
	8	-5		8	-1.46
	9	0.91		9	0.02
	10	-0.36		10	-0.43
	11	3.46		11	-0.7
	12	-0.61		12	0.08
	13	4.47		13	1.79
	14	1.61		14	-0.06
	15	0.73		15	0.44
	16	1.61		16	0.2
Stroop task reaction time	1	-381.51			
	2	120.33			
	3	-66.81			
	4	-125.70			
	5	-99.21			
	6	-169.24			
	7	-166.75			

8	-35.52
9	-5.97
10	-179.12
11	39.43
12	-145.14
13	153.61
14	295.5
15	687.17
16	-254.57

The main and interaction effects are presented in Table 5.6. A significant effect of time was observed for perceived MF, motivation, PF, tiredness, BRUMSF, and BRUMSC. As shown in Table 5.7, the Bonferroni post-hoc tests revealed significant increases in perceived MF, PF, tiredness, BRUMSF, and BRUMSC, while motivation declined after the orienteering competition. Although a significant time*gender interaction was found for BRUMSV (Table 5.6), the Bonferroni post-hoc analysis did not report a significant difference between male and female participants ($p = 0.097$). However, no significant changes were observed in Stroop task reaction time before and after the competition. Additionally, the overall fixed effects model for the Stroop task response accuracy was not significant ($F(3, 82) = 0.26$, $p = 0.856$). There were no significant effects of time ($\beta = -0.29$, SE = 0.68, $t(82) = -0.43$, $p = 0.67$, gender ($\beta = -0.44$, SER = 0.73, $t(82) = -0.60$, $p = 0.549$) or interaction effects between time and gender ($\beta = 0.17$, SE = 0.46, $t(82) = 0.38$, $p = 0.705$).

Table 5.6 The summary of the fixed and interaction effects for all outcome variables before and after orienteering competition.

Variable	Effects	F-value	df	p
MF	Time	25.89	1, 68.8	< 0.001**
	Gender	2.48	1, 14.1	0.138
	Time*Gender	1.91	1, 68.8	0.171
Motivation	Time	6.87	1, 68.9	0.011*
	Gender	1.09	1, 14	0.314
	Time*Gender	0.49	1, 68.9	0.488
PF	Time	51.5	1, 68.5	< 0.001**
	Gender	3.75	1, 14	0.073
	Time*Gender	0	1, 68.5	0.965
Stress	Time	2.6	1, 67.9	0.111
	Gender	0.35	1, 13.4	0.565
	Time*Gender	0	1, 67.9	0.953
Tiredness	Time	10.81	1, 68.7	0.002*
	Gender	3.9	1, 13.7	0.069
	Time*Gender	3.77	1, 68.7	0.056
BRUMSV	Time	2.94	1, 69.8	0.091
	Gender	3.22	1, 14.7	0.094
	Time*Gender	7.66	1, 69.8	0.007*
BRUMSF	Time	17.49	1 ,68.8	< 0.001**
	Gender	1.81	1, 14.6	0.199
	Time*Gender	1.28	1, 68.8	0.261
BRUMSC	Time	5.16	1, 15.3	0.038*
	Gender	2.82	1, 14.1	0.115
	Time*Gender	0.38	1, 15.3	0.546
Stroop task	Time	1.1	1, 68.5	0.298
reaction time	Gender	0.04	1, 14.4	0.853
	Time*Gender	0.08	1, 68.5	0.773

*: p < 0.05 **; p < 0.001.

Table 5.7 The Bonferroni post-hoc comparison of the variables before and after orienteering competition.

Comparison	Variable	Estimate (β) ± SE	df	t	p	95%CI	Cohen's d	Descriptor
POST vs PRE	MF	20.8 ± 4.09	68.2	5.09	<0.001**	12.6, 29	1.12	Moderate
POST vs PRE	Motivation	-9.8 ± 3.74	68.3	-2.62	0.011*	-17.3, -2.3	0.58	Small
POST vs PRE	PF	28.1 ± 3.91	68.2	7.18	<0.001**	20.3, 35.9	1.59	Large
POST vs PRE	Tiredness	15.1 ± 4.6	68.3	3.29	0.002*	5.9, 24.3	0.72	Moderate
POST vs PRE	BRUMSF	2.64 ± 0.63	68.1	4.18	< 0.001**	1.4, 3.9	0.92	Moderate
POST vs PRE	BRUMSC	1.73 ± 0.77	13.1	2.25	0.042	0.1, 3.4	0.77	Moderate

SE: Standard errors; df: degree of freedom; *: $p < 0.05$ **; $p < 0.001$.

Pre, post and 24-hour after sprint (12 races), middle-distance (13 races) and long-distance (10 races) orienteering competition

According to Table 5.8, the random intercept model was preferred for most outcome variables (MF, motivation, PF, tiredness, stress, BRUMSV, BRUMSF, and the reaction time of Stroop task) across sprint, middle, and long-distance orienteering races. This suggests significant individual variability, and the inclusion of random intercepts significantly improved the model fit. However, the ratings for BRUMSC in middle- ($\chi^2 = 2.59$, $p = 0.108$) and long-distance races ($\chi^2 = 0.69$, $p = 0.408$) and the response accuracy of Stroop task in the sprint ($\chi^2 = 1.08$, $p = 0.298$) and long-distance ($\chi^2 = 0.98$, $p = 0.322$) races did not show a significant improvement with the random intercept model compared to the fixed-effects model. Consequently, fixed-effects models were applied to these two variables, while the random intercept model was used for the remaining variables in further analysis.

Table 5.8 The summary of the comparison between random intercept models and fixed-effects models across different race types.

Variable	Race Type	χ^2	P
MF	Sprint	14.32	< 0.001
	Middle	19.42	< 0.001
	Long	16.22	< 0.001
Motivation	Sprint	21.14	< 0.001
	Middle	25.24	< 0.001
	Long	14.75	< 0.001
PF	Sprint	14.23	< 0.001
	Middle	25.44	< 0.001
	Long	16.08	< 0.001
Tiredness	Sprint	14.23	< 0.001
	Middle	17.14	< 0.001
	Long	16.56	< 0.001
Stress	Sprint	32.8	< 0.001
	Middle	33.68	< 0.001
	Long	16.84	< 0.001
BRUMSV	Sprint	10.45	< 0.001
	Middle	5.02	0.025
	Long	4.39	0.036
BRUMSF	Sprint	18.87	< 0.001
	Middle	20.18	< 0.001
	Long	14.75	< 0.001
BRUMSC	Sprint	3.85	0.049
Stroop task reaction time	Sprint	71.67	< 0.001
	Middle	70.15	< 0.001
	Long	54.42	< 0.001
Stroop task response accuracy	Middle	7.99	0.005

After comparing the random intercept model with the random intercept plus time and/or gender random slope models, the selected model is presented in Table 5.9. The random intercept model provided the best balance of model fit and simplicity without unnecessary model complexity for most variables across different race types. However, for the Stroop task response accuracy in middle-distance races, the random intercept plus gender random slope model demonstrated a significant model improvement than other models. Although the random intercept plus time random slope models reported better model fit in the ratings of motivation (AIC = 407.91, BIC = 421, χ^2 = 16.36) and tiredness (AIC = 424.09, BIC = 437.19, χ^2 = 8.68) in the sprint race, and the reaction time of the Stroop task (AIC = 553.85, BIC = 565.67, χ^2 = 4.17) in the long-distance race compared to random intercept model, there were convergence issues where degrees of freedom were presented as zero and no significance value was reported. This indicates that the model may have been overfitting and was not ideal for the analysis. Therefore, the random intercept models were used for MF, motivation, PF, stress, tiredness, BRUMSV, BRUMSF and the reaction time of the Stroop task for the sprint, middle-, and long-distance orienteering races. Additionally, the random intercept model was applied to analyse BRUMSC in sprint races. For the response accuracy of the Stroop task in middle-distance orienteering races, the random intercept plus gender random slope model was used for further analysis.

Table 5.9 The selected model for each outcome variable across different race types based on model comparison.

Variable	Race type	Selected Model	AIC	BIC	Log-likelihood	χ^2	df	p
MF	Sprint	Random Intercept (Participant ID)	429.12	438.48	-209.56	-	-	-
	Middle	Random Intercept (Participant ID)	457.82	467.58	-223.91	-	-	-
	Long	Random Intercept (Participant ID)	358.36	366.80	-174.18	-	-	-
Motivation	Sprint	Random Intercept (Participant ID)	420.27	429.63	-205.13	-	-	-
	Middle	Random Intercept (Participant ID)	450.92	460.67	-220.46	-	-	-
	Long	Random Intercept (Participant ID)	362.44	370.88	-176.22	-	-	-
PF	Sprint	Random Intercept (Participant ID)	436.13	445.48	-213.06	-	-	-
	Middle	Random Intercept (Participant ID)	463.14	472.90	-226.57	-	-	-
	Long	Random Intercept (Participant ID)	381.66	390.11	-185.83	-	-	-
Stress	Sprint	Random Intercept (Participant ID)	419.96	429.32	-204.98	-	-	-
	Middle	Random Intercept (Participant ID)	459.67	469.43	-224.84	-	-	-
	Long	Random Intercept (Participant ID)	356.09	364.53	-173.04	-	-	-
Tiredness	Sprint	Random Intercept (Participant ID)	428.77	438.12	-209.38	-	-	-
	Middle	Random Intercept (Participant ID)	466.98	476.73	-228.49	-	-	-
	Long	Random Intercept (Participant ID)	372.90	381.34	-181.45	-	-	-
BRUMSV	Sprint	Random Intercept (Participant ID)	242.58	251.93	-116.29	-	-	-
	Middle	Random Intercept (Participant ID)	279.52	289.28	-134.76	-	-	-
	Long	Random Intercept (Participant ID)	210.01	218.46	-100.01	-	-	-
BRUMSF	Sprint	Random Intercept (Participant ID)	242.58	251.93	-116.29	-	-	-
	Middle	Random Intercept (Participant ID)	283.16	292.92	-136.58	-	-	-
	Long	Random Intercept (Participant ID)	228.65	237.09	-109.33	-	-	-
BRUMSC	Sprint	Random Intercept (Participant ID)	212.43	221.78	-101.21	-	-	-
Stroop task reaction time	Sprint	Random Intercept (Participant ID)	666.30	675.66	-328.15	-	-	-
	Middle	Random Intercept (Participant ID)	700.78	710.54	-345.39	-	-	-
	Long	Random Intercept (Participant ID)	555.45	563.89	-272.72	-	-	-
Stroop task response accuracy	Middle	Random Slope: Participant x Gender	112.42	126.08	-49.21	7.40	2	0.025

The random intercepts for each participant were examined across sprint, middle- and long-distance races. There was noticeable individual variability in the ratings of MF (Sprint: -7.60 to 7.38; Middle-distance: -13.54 to 14.74; Long-distance: -11.33 to 10.08), motivation (Sprint: -16.15 to 10.09; Middle-distance: -23.95 to 14.2; Long-distance: -6.18 to 10.11), PF (Sprint: -5.32 to 10.29; Middle-distance: -20.22 to 21.85; Long-distance: -5.08 to 10.06), tiredness (Sprint: -5.27 to 7.28; Middle-distance: -11.86 to 12.81; Long-distance: -7.99 to 12.55), stress (Sprint: -29.99 to 26.87; Middle-distance: -16.45 to 24.21; Long-distance: -9.79 to 8.81), BRUMSV (Sprint: -1.76 to 3.43; Middle-distance: -1.18 to 1.87; Long-distance: -0.91 to 1.25), BRUMSF (Sprint: -4.42 to 4.52; Middle-distance: -4.82 to 4.96; Long-distance: -3.48 to 3.51), BRUMSC (Sprint: -0.8 to 1.52), and the reaction time of Stroop task (Sprint: -462.2ms to 763.62ms; Middle-distance: -366.39ms to 573.21ms; Long-distance: -333.88ms to 573.21ms). Finally, the response accuracy of the Stroop task in middle-distance races was -12.98 to 11.88. These findings further support the use of the random intercept model for analysis.

The main and interaction effects for the changes in outcome variables before, immediately after, and one day after sprint, middle-, and long-distance orienteering races are presented in Table 5.10, with the results of the Bonferroni post hoc test summarised in Table 5.11. Although the ratings of motivation and the reaction time of the Stroop task reported significant effects of time, the Bonferroni post-hoc test was not significant ($p > 0.05$). A significant interaction effect between time and gender was reported in stress ratings in sprint races. The Bonferroni post hoc test revealed that female participants demonstrated significantly lower stress ratings at POST compared to both PRE1 and PRE, but significantly higher ratings in MD+1 compared to POST. In long-distance races, a significant main effect of gender was reported in stress ratings, and the Bonferroni post hoc test indicates female participants reported significantly higher stress ratings than male participants.

For BRUMSC, the overall fixed effects models were not significant for either middle- ($F(3, 48) = 1.69$, $p = 0.181$) or long-distance races ($F(3, 36) = 1.87$, $p = 0.153$). In the middle-distance races, there were no significant effects of time ($\beta = -0.63$, SE = 0.83, $t(48) = -0.75$, $p = 0.456$), gender ($\beta = -0.25$, SE = 1.48, $t(48) = -0.17$, $p = 0.866$), or interaction effects between gender and time ($\beta = 0.55$, SE = 0.54, $t(48) = 1.03$, $p = 0.309$). Similar in long-distance races, no significant effects of time ($\beta = 0.08$, SE = 1.02, $t(36) = 0.07$, $p = 0.942$), gender ($\beta = 1.42$, SE = 1.89, $t(36) = 0.75$, $p = 0.459$), or interaction effects between gender and time ($\beta = 0.13$, SE = 0.69, $t(36) = 0.18$, $p = .857$) were reported. Moreover, the overall fixed effects models for the

Stroop task response accuracy were not significant in sprint (F(3, 44) = 0.07, p = 0.978) and long-distance races (*F*(3, 36) = 0.24, p = 0.865). In the sprint races, there were no significant effects of time (β = 0, SE = 0.30, t(44) = 0, p = 1.00), gender (β = -0.13, SE = 0.57, *t*(44) = -0.22, p = 0.829) or interaction effects between gender and time (β = 0.03, SE = 0.21, t(44) = 0.12, p = 0.906). Similarly, no significant effects of time (β = 0.20, SE = 0.47, t(36) = 0.43, p = 0.672), gender (β = 0.13, SE = 0.87, t(36) = 0.15, p = 0.886) or interaction effects between gender and time (β = -0.15, SE = 0.32, t(36) = -0.48, p = 0.638) found in long-distance races.

Table 5.10 The summary of LMM results for outcome variables measured before, immediately after, and one day after sprint, middle-, and long-distance orienteering races.

Race type	Variable	Fixed Effects	F-value	df	p
Sprint	MF	Time	7.66	3, 30	< 0.001*
		Gender	1.24	1, 10	0.292
		Time*Gender	0.99	3, 30	0.412
	Motivation	Time	1.01	3, 30	0.401
		Gender	0	1, 10	0.952
		Time*Gender	1.94	3, 30	0.145
	PF	Time	7.64	3, 30	< 0.001*
		Gender	2.14	1, 10	0.174
		Time*Gender	0.38	3, 30	0.768
	Stress	Time	5.09	3, 30	0.006*
		Gender	0.05	1, 10	0.832
		Time*Gender	5.75	3, 30	0.003*
	Tiredness	Time	0.46	3, 30	0.711
		Gender	0.18	1, 10	0.677
		Time*Gender	0.2	3, 30	0.893
	BRUMSV	Time	2.08	3, 30	0.124
		Gender	1.14	1, 10	0.311
		Time*Gender	0.45	3, 30	0.72
	BRUMSF	Time	1.2	3, 30	0.326
		Gender	0.29	1, 10	0.602
		Time*Gender	0.29	3, 30	0.830
	BRUMSC	Time	0.28	3, 30	0.841
		Gender	0.25	1, 10	0.627
		Time*Gender	1.61	3, 30	0.207
	Stroop task reaction time	Time	3.48	3, 30	0.028*
		Gender	0.39	1, 10	0.55
		Time*Gender	7.28	3, 30	< 0.001*
Middle	MF	Time	8.05	3, 33	< 0.001*
		Gender	0.58	1, 11	0.461
		Time*Gender	0.07	3, 33	0.978
	Motivation	Time	5.69	3, 33	0.003*
		Gender	1	1, 11	0.34
		Time*Gender	0.67	3, 33	0.574
	PF	Time	16.1	3, 33	< 0.001*
		Gender	2.16	1, 11	0.169
		Time*Gender	0.61	3, 33	0.611
	Stress	Time	2.08	3, 33	0.121
		Gender	0.57	1, 11	0.465

		Time*Gender	0.44	3, 33	0.728
	Tiredness	Time	3.56	3, 33	0.024*
		Gender	0.99	1, 11	0.34
		Time*Gender	1.83	3, 33	0.161
	BRUMSV	Time	2.79	3, 33	0.056
		Gender	0.12	1, 11	0.736
		Time*Gender	1.97	3, 33	0.137
	BRUMSF	Time	4.49	3, 33	0.009*
		Gender	0.11	1, 11	0.75
		Time*Gender	2.11	3, 33	0.118
	Stroop task reaction time	Time	4.88	3, 33	0.006*
		Gender	0.13	1, 11	0.724
		Time*Gender	1.81	3, 33	0.165
	Stroop task response accuracy	Time	0.67	3, 39	0.575
		Gender	0.02	1, 5.9	0.882
		Time*Gender	0.36	3, 39	0.781
Long	MF	Time	13.55	3, 24	< 0.001*
		Gender	2.24	1, 8	0.173
		Time*Gender	2.37	3, 24	0.096
	Motivation	Time	3.14	3, 24	0.044*
		Gender	0.02	1, 8	0.886
		Time*Gender	0.63	3, 24	0.604
	PF	Time	10.57	3, 24	< 0.001*
		Gender	2.73	1, 8	0.137
		Time*Gender	0.34	3, 24	0.796
	Stress	Time	0.98	3, 24	0.421
		Gender	6.17	1, 8	0.038*
		Time*Gender	0.67	3, 24	0.581
	Tiredness	Time	6.31	3, 24	0.003*
		Gender	1.24	1, 8	0.297
		Time*Gender	0.54	3, 24	0.662
	BRUMSV	Time	7.32	3, 24	0.001*
		Gender	0.31	1, 8	0.595
		Time*Gender	1.46	3, 24	0.252
	BRUMSF	Time	5.46	3, 24	0.005*
		Gender	0.24	1, 8	0.638
		Time*Gender	0.55	3, 24	0.655
	Stroop task reaction time	Time	3.12	3, 24	0.045*
		Gender	0.01	1, 8	0.91
		Time*Gender	1.35	3, 24	0.282

*: $p < 0.05$.

Table 5.11 The Bonferroni post-hoc comparison of the variables before, immediately after and one day after sprint, middle- and long-distance orienteering races.

Comparison	Race Type	Variable	Estimate (β) ± SE	df	t	p	95%CI	Cohen's d	Descriptor
POST vs PRE1	Sprint	MF	26.62 ± 6.78	30	3.93	0.003	12.8, 40.5	1.7	Large
		PF	33.81 ± 7.72	30	4.38	< 0.001	18, 49.6	1.9	Large
		Stress	-15.44 ± 4.89	30	-3.16	0.022	-25.4, -5.5	1.37	Large
	Middle	MF	25.32 ± 5.55	33	4.56	< 0.001	14, 36.6	1.8	Large
		Motivation	-20.5 ± 5.46	33	-3.75	0.004	-31.6, -9.38	1.48	Large
		PF	34.5 ± 5.43	33	6.36	< 0.001	23.4, 45.6	2.5	Very large
		Tiredness	19.24 ± 6.73	33	2.86	0.044	5.5, 32.9	1.13	Moderate
		BRUMSF	2.93 ± 1.02	33	2.86	0.044	0.9, 5	1.13	Moderate
		RT	-170.51 ± 51.8	33	-3.29	0.014	-275.9, -65.1	1.29	Large
	Long	MF	38.21 ± 6.65	24	5.74	< 0.001	24.5, 51.9	2.62	Very large
		PF	51.9 ± 9.52	24	5.45	< 0.001	32.2, 71.6	2.48	Very large
		Tiredness	36.83 ± 9.19	24	4.01	0.003	17.8, 55.8	1.83	Large
		BRUMSV	-5 ± 1.25	24	-4.01	0.003	-7.6, -2.4	1.83	Large
		BRUMSF	5.33 ± 1.34	24	3.98	0.003	2.56, 8.1	1.81	Large
POST vs PRE	Sprint	MF	29.31 ± 6.78	30	4.32	< 0.001	15.5, 43.2	1.87	Large
		PF	28.62 ± 7.72	30	3.71	0.005	12.9, 44.4	1.6	Large
		Stress	-16.06 ± 4.89	30	-3.29	0.016	-26.1, -6.1	1.42	Large
	Middle	MF	21.44 ± 5.55	33	3.86	0.003	10.1, 32.7	1.52	Large
		PF	26.48 ± 5.43	33	4.88	< 0.001	15.4, 37.5	1.92	Large
	Long	MF	28 ± 6.65	24	4.21	0.002	14.3, 41.7	1.92	Large
		PF	33.4 ± 9.52	24	3.5	0.011	13.7, 53.1	1.6	Large
		Tiredness	29.25 ± 9.19	24	3.18	0.024	10.3, 48.2	1.46	Large
MD+1 vs POST	Sprint	MF	20.56 ± 6.78	30	3.03	0.03	6.7, 34.4	1.31	Large
		Stress	15.25 ± 4.89	30	3.12	0.024	5.3, 25.2	1.35	Large
MD+1 vs PRE1	Middle	PF	23.02 ± 5.43	33	4.24	0.001	12, 34.1	1.67	Large
		RT	-172.59 ± 51.8	33	-3.33	0.013	-278, -67.2	1.31	Large
	Long	MF	28.62 ± 6.65	24	4.3	0.001	14.9, 42.4	1.96	Large
		PF	32.1 ± 9.52	24	3.37	0.015	12.4, 51.8	1.54	Large
		BRUMSV	-4.79 ± 1.25	24	-3.85	0.005	-7.4, -2.2	1.75	Large
POST vs PRE1 (F)	Sprint	Stress	-30.5 ± 7.98	30	-3.82	0.017	-46.8, -14.2	2.7	Very large

POST vs PRE (F)	Sprint	Stress	-30.75 ± 7.98	30	-3.85	0.016	-47.1, -14.5	2.72	Very large
MD+1 vs POST (F)	Sprint	Stress	34 ± 7.98	30	4.26	0.005	17.7, 50.3	3.01	Very large
MD+1 vs PRE1 (F)	Sprint	RT	330.17 ± 94.2	30	-3.5	0.041	137.8, 522.6	2.48	Very large
Female vs Male	Long	Stress	22 ± 8.84	8	2.48	0.038	1.62, 42.38	1.3	Large

PRE1: Before the first day of the competition; PRE: Before the specific type of race; POST: Immediately after the race; MD+1: one day after the race; F: Female; RT: The reaction time of the Stroop task.

Changes after the termination of orienteering competition

The analysis of model fit for POST, 24POST and 48POST orienteering competition demonstrates that the inclusion of random intercepts for ID improved the model fit compared to the fixed-effects model only for all outcome variables. Specifically, the ratings of MF ($\chi^2(1) = 32.59$, $p < 0.001$), motivation ($\chi^2(1) = 26.98$, $p < 0.001$), PF ($\chi^2(1) = 24.63$, $p < 0.001$), tiredness ($\chi^2(1) = 27.9$, $p < 0.001$), stress ($\chi^2(1) = 21.15$, $p < 0.001$), BRUMSV ($\chi^2(1) = 5.54$, $p = 0.01857$), BRUMSF ($\chi^2(1) = 24.234$, $p < 0.001$), BRUMSC ($\chi^2(1) = 10$, $p = 0.002$), the reaction time ($\chi^2(1) = 53.06$, $p < 0.001$), and response accuracy of Stroop task ($\chi^2(1) = 5.34$, $p = 0.021$) all showed significant improvements in model fit with the addition of random intercepts. These findings highlight the importance of accounting for individual-level variability across all variables. Due to the convergence issues, the random intercept plus gender and time random slopes model encounter model fit warning, suggesting potential instability and complexity issues. Therefore, the analysis focused on the random intercept plus gender random slope model and the random intercept plus time random slope model. According to the model comparison for POST, 24POST and 48POST orienteering competition, Table 5.12 indicates that the random intercept model provided the best model fit compared to the random intercept plus random slope models. For most the variables including motivation, PF, tiredness, stress, BRUMSV, BRUMSF, BRUMSC, and the reaction time of the Stroop task**,** the random intercept model was preferred. Although the random intercept plus time random slope model for the ratings of MF and Stroop task response accuracy showed a lower AIC and BIC compared to the random intercept model, this does not offer significant improvements in model fit or result in convergence issues. Therefore, these results indicate the random intercept model is the best fit for all outcome variables.

Table 5.12 The model comparison for the changes after the termination of the orienteering competition.

Variable	Model	AIC	BIC	Log-likelihood	χ²	df	p
MF	Random Intercept (Participant ID)	432.10	441.45	-211.05	-	-	-
	Random Slope: Participant x Gender	434.38	447.48	-210.19	1.72	2	0.424
	Random Slope: Participant x Time	426.90	440.00	-206.45	7.48	0	N/A
Motivation	Random Intercept (Participant ID)	447.80	457.15	-218.90	-	-	-
	Random Slope: Participant x Gender	451.78	464.87	-218.89	0.02	2	0.989
	Random Slope: Participant x Time	451.64	464.74	-218.82	0.14	0	-
PF	Random Intercept (Participant ID)	441.66	451.01	-215.83	-	-	-
	Random Slope: Participant x Gender	444.02	457.11	-215.01	1.64	2	0.44
	Random Slope: Participant x Time	445.50	458.60	-215.75	0	0	-
Stress	Random Intercept (Participant ID)	437.21	446.57	-213.61	-	-	-
	Random Slope: Participant x Gender	441.21	454.31	-213.61	0	2	1
	Random Slope: Participant x Time	439.06	452.16	-212.53	2.15	0	-
Tiredness	Random Intercept (Participant ID)	452.00	461.36	-221.00	-	-	-
	Random Slope: Participant x Gender	453.94	467.04	-219.97	2.07	2	0.356
	Random Slope: Participant x Time	455.32	468.42	-220.66	0	0	-
BRUMSV	Random Intercept (Participant ID)	265.90	275.26	-127.95	-	-	-
	Random Slope: Participant x Gender	268.96	282.06	-127.48	0.94	2	0.625
	Random Slope: Participant x Time	265.75	278.84	-125.87	3.22	0	-
BRUMSF	Random Intercept (Participant ID)	259.00	268.35	-124.50	-	-	-
	Random Slope: Participant x Gender	262.96	276.05	-124.48	0.04	2	0.98
	Random Slope: Participant x Time	262.29	275.39	-124.15	0.66	0	-
BRUMSC	Random Intercept (Participant ID)	244.90	254.25	-117.45	-	-	-
	Random Slope: Participant x Gender	244.31	257.41	-115.15	4.59	2	0.101
	Random Slope: Participant x Time	238.85	251.95	-112.43	5.46	0	-
Stroop task reaction time	Random Intercept (Participant ID)	655.18	664.53	-322.59	-	-	-
	Random Slope: Participant x Gender	657.70	670.80	-321.85	1.48	2	0.477
	Random Slope: Participant x Time	659.10	672.20	-322.55	0	0	-
Stroop task response accuracy	Random Intercept (Participant ID)	127.12	136.48	-58.56	-	-	-
	Random Slope: Participant x Gender	131.01	144.11	-58.51	0.11	2	0.946
	Random Slope: Participant x Time	119.39	132.49	-52.7	11.62	0	-

According to Table 5.13, it is observed that there is noticeable individual variability across participants in most of the outcome variables except the Stroop task response accuracy. The Stroop task response accuracy failed to capture meaningful individual variability because there was little to no variation in the accuracy scores across participants, leading the model to assign zero variance. Conversely, the random intercept estimates for each participant from the overall mean for the ratings of MF ranged from -31.32 to 32.16. Similar variability was also observed in motivation, PF, tiredness and stress. These findings highlight the importance of incorporating a random intercept model to assess the variability in the outcome variables for the POST, 24POST and 48POST orienteering competition time points.

Table 5.13 The random intercepts estimate of each participant based on the changes after the termination of orienteering competition Linear Mixed Model.

Variable	ID	Random intercept estimate	Variable	ID	Random intercept estimate
MF	1	-13.12	Motivation	1	-7.91
	2	32.16		2	-10.36
	3	-4.47		3	-6
	4	10.07		4	-3.17
	5	14.01		5	-19.73
	6	-15.08		6	-19.73
	7	0.31		7	21.89
	8	27.44		8	-24.61
	9	-12.28		9	19.06
	10	-10.04		10	15.98
	11	11.22		11	-2
	12	-7.52		12	13.93
	13	-31.32		13	24.32
	14	-20.7		14	16.62
	15	14.26		15	-21.41
	16	5.06		16	3.13
PF	1	-16.7	Tiredness	1	-7.25
	2	10.79		2	23.9
	3	-3.79		3	-11.69
	4	8.81		4	16.25
	5	4.05		5	10.41
	6	-8.8		6	-22.01
	7	22.34		7	-18.06
	8	29.01		8	26.75
	9	-13		9	-14.63
	10	-4.10		10	4.35
	11	-10.28		11	9.36
	12	-18.43		12	-6.99
	13	1.89		13	-14.85
	14	-19.11		14	-14.85
	15	1.4		15	1.23
	16	15.91		16	18.06
Stress	1	5.32	BRUMSV	1	2.36
	2	28.18		2	-1.65

	3	8.65		3	0.08
	4	4.96		4	-0.08
	5	-0.98		5	-1.42
	6	-13.13		6	-0.32
	7	-5.1		7	0.95
	8	-8.57		8	-2.05
	9	-15.74		9	0.95
	10	8.57		10	0.47
	11	8.57		11	-1.42
	12	13.13		12	0.16
	13	-21.09		13	1.34
	14	-8.28		14	0.08
	15	-12.41		15	0.24
	16	7.92		16	0.32
BRUMSF	1	-3.88	BRUMSC	1	-1.04
	2	4.28		2	4.53
	3	-4		3	-2.67
	4	2.86		4	-0.58
	5	2.11		5	0.12
	6	-7.43		6	-0.81
	7	-1.03		7	-0.58
	8	4.4		8	-1.04
	9	-4.74		9	-1.04
	10	2.97		10	0.35
	11	1.54		11	0.81
	12	-3.31		12	1.04
	13	-2		13	-1.04
	14	-3.42		14	-1.04
	15	-1.14		15	0.81
	16	-2.69		16	2.21
Stroop task reaction time	1	-389.15			
	2	19			
	3	-12.32			
	4	260.85			
	5	111.47			
	6	-194.58			
	7	373.18			
	8	56.27			
	9	48.44			
	10	-232.85			
	11	-38.18			
	12	-71.26			
	13	52.28			
	14	-162.26			
	15	-157.56			
	16	336.67			

The main and interaction effects for the changes after the termination of the orienteering competition are presented in Table 5.14. A significant effect of time was observed from the final orienteering competition to 48POST for perceived MF, PF, tiredness, BRUMSV, BRUMSF, and BRUMSC as shown in Table 5.14. However, gender and interaction effects were not significant for any outcome variable. The Bonferroni post-hoc tests revealed that ratings of perceived MF, PF, tiredness, BRUMSF, and BRUMSC significantly decreased at 48POST compared to immediately after the final competition, while the changes in BRUMSV were insignificant (Table 5.15).

Table 5.14 The summary of the fixed effects for all outcome variables based on changes after the termination of the orienteering competition.

Variable	Fixed Effects	F-value	df	p
MF	Time	7.88	2, 28	0.002*
	Gender	2.44	1, 14	0.141
	Time*Gender	1.02	2, 288	0.372
Motivation	Time	2.7	2, 28	0.085
	Gender	0.07	1, 14	0.79
	Time*Gender	1.71	2, 28	0.199
PF	Time	14.71	2, 28	< 0.001**
	Gender	2.3	1, 14	0.152
	Time*Gender	1.56	2, 28	0.228
Stress	Time	0.86	2, 28	0.432
	Gender	1.72	1, 14	0.21
	Time*Gender	0.39	2, 28	0.683
Tiredness	Time	10.63	2, 28	< 0.001**
	Gender	2.67	1, 14	0.076
	Time*Gender	2.23	2, 28	0.126
BRUMSV	Time	3.44	2, 28	0.046*
	Gender	3.55	1, 14	0.08
	Time*Gender	2.09	2, 28	0.142
BRUMSF	Time	10.71	2, 28	< 0.001**
	Gender	0.89	1, 14	0.361
	Time*Gender	1.32	2, 28	0.283
BRUMSC	Time	4.76	2, 28	0.017*
	Gender	3.32	1, 14	0.09
	Time*Gender	0.99	2, 28	0.384
Stroop task reaction time	Time	1.34	2, 28	0.277
	Gender	0.19	1, 14	0.673
	Time*Gender	1.19	2 , 28	0.318
Stroop task response accuracy	Time	0.47	2, 42	0.631
	Gender	0.96	1, 42	0.332
	Time*Gender	0.03	2, 42	0.971

df: degree of freedom; *: p < 0.05 **; p < 0.001.

Table 5.15 The Bonferroni post-hoc comparison of the variables immediately post, 24-hour and 48-hour post orienteering competition.

Comparison	Variable	Estimate (β) ± SE	df	t	p	95%CI	Cohen's d	Descriptor
POST vs PRE1	MF	33.07 ± 5.95	42	5.56	< 0.001**	21.1, 45.1	2.03	Very large
	Motivation	-19.23 ± 6.82	42	-2.82	0.044*	-33, -5.5	-1.03	Moderate
	PF	45.03 ± 6.99	42	6.44	< 0.001**	30.9, 59.1	2.35	Very large
	Tiredness	30.23 ± 6.53	42	4.63	< 0.001**	17.1, 43.1	1.69	Large
	BRUMSV	-4.15 ± 1.05	42	-3.95	0.002*	-6.3, -2	-1.45	Large
	BRUMSF	4.95 ± 0.92	42	5.39	< 0.001**	3.1, 6.8	1.97	Large
	BRUMSC	2.65 ± 0.87	42	3.05	0.024*	0.9, 4.4	1.11	Moderate
24POST vs PRE1	MF	23.72 ± 5.95	42	3.99	0.002*	11.7, 35.7	1.46	Large
	Motivation	-27.03 ± 6.82	42	-3.97	0.002*	-40.8, -13.2	-1.45	Large
	PF	37.37 ± 6.99	42	5.34	< 0.001**	23.3, 51.5	1.95	Large
	Tiredness	25.43 ± 6.53	42	3.89	0.002	12.3, 38.6	1.42	Large
	BRUMSV	-4.43 ± 1.05	42	-4.22	< 0.001**	-6.6, -2.3	-1.54	Large
	BRUMSF	4.13 ± 0.92	42	4.5	< 0.001**	2.3, 6	1.65	Large
48POST vs PRE1	RT	-198.9 ± 55.7	42	-3.57	0.006*	-311.3, -86.5	-1.3	Large
48POST vs POST	MF	-21.95 ± 5.95	42	-3.69	0.004*	-34, -9.9	-1.35	Large
	PF	-33.02 ± 6.99	42	-4.72	< 0.001**	-47.1, -18.9	-1.72	Large
	Tiredness	-24.73 ± 6.53	42	-3.79	0.003*	-37.9, 11.6	-1.38	Large
	BRUMSF	-3.78 ± 0.92	42	-4.12	0.001*	-5.6, -1.9	-1.51	Large
	BRUMSC	-2.65 ± 0.87	42	-3.05	0.024*	-4.4, -0.9	-1.11	Moderate
48POST vs 24POST	Tiredness	-19.93 ± 6.53	42	-3.05	0.024*	-33.1, -6.8	-1.11	Moderate
	BRUMSF	-2.97 ± 0.92	42	-3.23	0.014*	-4.8, -1.1	-1.18	Moderate

SE: Standard errors; df: degree of freedom; RT: The reaction time of Stroop task; *: p < 0.05 **; p < 0.001.

Comparison between first day, final competition, 24-hour and 48-hour after orienteering competition

The likelihood ratio tests comparing fixed effects models and random intercepts model revealed significant improvements in model fit for MF ($\chi^2(1) = 19.38$, $p < 0.001$), motivation ($\chi^2(1) = 20.9$, $p < 0.001$), PF ($\chi^2(1) = 14.92$, $p < 0.001$), tiredness ($\chi^2(1) = 16.05$, $p < 0.001$), stress ($\chi^2(1) = 24.21$, $p < 0.001$), BRUMSF ($\chi^2(1) = 16.32$, $p < 0.001$), BRUMSC ($\chi^2(1) = 4.43$, $p = 0.035$), Stroop task reaction time ($\chi^2(1) = 63.18$, $p < 0.001$), and Stroop task response accuracy ($\chi^2(1) = 7.03$, $p = 0.008$). For BRUMSV, the improvement was marginal ($\chi^2(1) = 3.65$, $p = 0.056$). These results indicate that including random intercepts significantly improved model fits for most outcome variables, highlighting the importance of accounting for individual variability. For BRUMSV, although the improvement in model fit was not statistically significant ($p > 0.05$), the inclusion of random intercepts is still justified for further analysis due to the focus on individual differences of this thesis. The marginal p-value suggests some variability between participants that could be informative for understanding individual responses and using the random intercept model would better capture this variability, making it a reasonable choice for further analysis.

The model comparison in Table 5.16 reveals that the random intercept model provides the best fit for all outcome variables with no significant improvement when adding a random slope for time, gender or both time and gender. Although the AIC and BIC of the random intercept plus random slope for the time model were lower than the random intercept model for the ratings of MF, no significant improvement in model fits was reported and no degrees of freedom was reported, suggesting the model has a convergence issue. Accordingly, the random intercept model for all outcome variables was utilised for further analysis.

Table 5.16 The model comparison for the changes between before the first day of orienteering competition and immediately after the final orienteering competition.

Variable	Model	AIC	BIC	Log-likelihood	χ^2	df	p
MF	Random Intercept (Participant ID)	592.36	603.15	-291.18	-	-	-
	Random Slope: Participant x Gender	594.53	609.64	-290.26	1.83	2	0.401
	Random Slope: Participant x Time	591.76	606.88	-288.88	2.76	0	0.133
	Random Slopes: Participant x Gender x Time	595.90	617.48	-287.95	1.87	3	0.600
Motivation	Random Intercept (Participant ID)	593.95	604.75	-291.98	-	-	-
	Random Slope: Participant x Gender	597.92	613.04	-291.96	0.03	2	0.985
	Random Slope: Participant x Time	593.07	608.18	-289.53	4.86	0	-
	Random Slopes: Participant x Gender x Time	599.07	620.66	-289.54	0	3	1
PF	Random Intercept (Participant ID)	619.24	630.03	-304.62	-	-	-
	Random Slope: Participant x Gender	623.22	638.34	-304.61	0.02	2	0.992
	Random Slope: Participant x Time	622.90	638.01	-304.45	0.32	0	-
	Random Slopes: Participant x Gender x Time	628.08	649.67	-304.04	0.82	3	0.844
Stress	Random Intercept (Participant ID)	596.78	607.58	-293.39	-	-	-
	Random Slope: Participant x Gender	600.78	615.89	-293.39	0	2	0.999
	Random Slope: Participant x Time	598.22	613.33	-292.11	2.56	0	-
	Random Slopes: Participant x Gender x Time	604.21	625.80	-292.11	0.01	3	1
Tiredness	Random Intercept (Participant ID)	589.38	600.18	-289.69	-	-	-
	Random Slope: Participant x Gender	591.52	606.63	-288.76	1.86	2	0.394
	Random Slope: Participant x Time	593.38	608.49	-289.69	0	0	-
	Random Slopes: Participant x Gender x Time	597.18	618.77	-288.59	2.2	3	0.532
BRUMSV	Random Intercept (Participant ID)	353.67	364.47	-171.84	-	-	-
	Random Slope: Participant x Gender	356.77	371.88	-171.39	0.9	2	0.638
	Random Slope: Participant x Time	355.63	370.75	-170.82	1.14	0	-
	Random Slopes: Participant x Gender x Time	360.91	382.50	-170.46	0.72	3	0.868
BRUMSF	Random Intercept (Participant ID)	364.08	374.87	-177.04	-	-	-
	Random Slope: Participant x Gender	368.08	383.19	-177.04	0	2	1
	Random Slope: Participant x Time	366.94	382.06	-176.47	1.13	0	-
	Random Slopes: Participant x Gender x Time	372.94	394.53	-176.47	0	3	1
BRUMSC	Random Intercept (Participant ID)	324.27	335.06	-157.13	-	-	-
	Random Slope: Participant x Gender	324.17	339.29	-155.09	4.09	2	0.129
	Random Slope: Participant x Time	328.13	343.25	-157.07	0	0	-
	Random Slopes: Participant x Gender x Time	330.04	351.63	-155.02	4.09	3	0.252

Stroop task reaction time	Random Intercept (Participant ID)	868.16	878.96	-429.08	-	-	-
	Random Slope: Participant x Gender	870.42	885.53	-428.21	1.74	2	0.419
	Random Slope: Participant x Time	870.99	886.10	-428.49	0	0	-
	Random Slopes: Participant x Gender x Time	872.27	893.86	-426.13	4.72	3	0.194
Stroop task response accuracy	Random Intercept (Participant ID)	162.39	173.18	-76.193	-	-	-
	Random Slope: Participant x Gender	166.17	181.28	-76.086	0.22	2	0.898
	Random Slope: Participant x Time	166.34	181.45	-76.169	0	0	-
	Random Slopes: Participant x Gender x Time	171.82	193.41	-75.912	0.51	3	0.916

The random intercept estimates for each variable for each participant are reported in Table 5.17. The result demonstrated considerable individual differences compared to the overall mean of most of the outcome variables except the ratings of BRUMSV and the response accuracy of the Stroop task. For example, the random intercept estimates for the ratings of MF and stress ranged from -18.61 to 20.44 and -21.53 to 26.85, respectively. Conversely, the response accuracy of the Stroop task showed no variation will all random intercept estimates at 0. These results emphasize the individual differences in overall mean scores across variables, highlighting the importance of accounting for random effects in these models.

Table 5.17 The random intercepts estimate of each participant based on before the first day, immediately after, 24-hour and 48-hour after the final orienteering competition Linear Mixed Model.

Variable	ID	Random intercept estimate	Variable	ID	Random intercept estimate
MF	1	-5.64	Motivation	1	-5.17
	2	20.44		2	-7.29
	3	-3		3	-7.46
	4	3.72		4	-0.19
	5	9.51		5	-11.12
	6	-9.08		6	-11.12
	7	-0.48		7	15.64
	8	14.2		8	-17.06
	9	-7.67		9	13.82
	10	-5.33		10	11.84
	11	8.57		11	-7.81
	12	-6.11		12	7.38
	13	-18.61		13	15.66
	14	-10.49		14	12.19
	15	7.94		15	-12.91
	16	2.01		16	3.58
PF	1	-3.57	Tiredness	1	-1.81
	2	5.19		2	11.05
	3	-1.51		3	-5.16
	4	1.64		4	7.78
	5	1.56		5	5.93
	6	-2.19		6	-8.35
	7	5.04		7	-8.95
	8	7.47		8	12.82
	9	-4.23		9	-7.14
	10	-0.81		10	3.51
	11	-1.86		11	3.15
	12	-5.21		12	-5.81
	13	2.37		13	-4.8
	14	-7.23		14	-7.46
	15	-0.46		15	-1.41
	16	3.79		16	6.65
Stress	1	9.79	BRUMSV	1	1.66
	2	26.85		2	-1.37

	3	9.82		3	-0.03
	4	6.19		4	0.17
	5	-0.18		5	-1.12
	6	-17.03		6	-0.71
	7	-5.07		7	0.94
	8	-0.54		8	-1.43
	9	-17.94		9	0.63
	10	6.89		10	0.11
	11	7.07		11	-0.92
	12	10.15		12	0.32
	13	-21.53		13	0.69
	14	-7.94		14	0.07
	15	-13.38		15	0.48
	16	6.89		16	0.53
BRUMSF	1	-2.91	BRUMSC	1	-0.57
	2	4.24		2	2.69
	3	-3.36		3	-1.79
	4	1.58		4	-0.57
	5	1.65		5	-0.03
	6	0.13		6	-0.43
	7	-1.2		7	-0.43
	8	3.55		8	-0.71
	9	-3.48		9	-0.71
	10	2.98		10	0.65
	11	1.08		11	0.38
	12	-2.91		12	0.52
	13	-1.08		13	-0.29
	14	-0.13		14	-0.43
	15	-1.27		15	0.38
	16	1.08		16	1.33
Stroop task reaction time	1	-380.11			
	2	99.43			
	3	22.34			
	4	231.02			
	5	79.38			
	6	-183.86			
	7	420.15			
	8	74.66			
	9	62.834			
	10	-247.03			
	11	-21.59			
	12	-97.41			
	13	-41.65			
	14	-155.42			
	15	-155.72			
	16	292.99			

The main and interaction effects for the comparison between PRE1, immediately after, 24- and 48-hour post-orienteering competition are presented in Table 5.18. A significant effect of time was observed for perceived MF, motivation, PF, tiredness, BRUMSV, BRUMSF, BRUMSC, and Stroop task reaction time, while stress and Stroop task accuracy remained unchanged as shown in Table 5.18. No significant effect of gender and interaction effects were reported in all outcome variables. The summary of the Bonferroni post-hoc test in Table 5.15 revealed that the most significant changes were found between immediately after the final orienteering competition and PRE1, as well as between 24POST and PRE1. The ratings for perceived MF, PF, tiredness, and BRUMSF were significantly higher immediately after the final competition and at 24POST compared to PRE1, while motivation and BRUMSV were significantly lower. Conversely, the reaction time of the Stroop task improved at 48POST, showing a significantly faster response than PRE1.

Table 5.18 The summary of the fixed and interaction effects for all outcome variables at PRE1, immediately after, 24 hours and 48 hours post-final orienteering competition.

Variable	Fixed Effects	F-value	df	p
MF	Time	11.81	3, 42	< 0.001**
	Gender	2.48	1, 14	0.138
	Time*Gender	1.33	3, 42	0.279
Motivation	Time	5.64	3, 42	0.002*
	Gender	0.09	1, 14	0.767
	Time*Gender	0.95	3, 42	0.427
PF	Time	18.26	3, 42	< 0.001**
	Gender	4.08	1, 14	0.063
	Time*Gender	0.9	3, 42	0.448
Stress	Time	0.66	3, 42	0.58
	Gender	1.3	1, 14	0.273
	Time*Gender	0.63	3, 42	0.601
Tiredness	Time	10.24	3, 42	< 0.001**
	Gender	4.43	1, 14	0.054
	Time*Gender	1.77	3, 42	0.168
BRUMSV	Time	8	3, 42	< 0.001*
	Gender	2.73	1, 14	0.121
	Time*Gender	2.25	3, 42	0.097
BRUMSF	Time	13.2	3, 42	< 0.001**
	Gender	0.6	1, 14	0.453
	Time*Gender	1.27	3, 42	0.296
BRUMSC	Time	4.7	3, 42	0.006*
	Gender	3.97	1, 14	0.066
	Time*Gender	0.98	3, 42	0.41
Stroop task reaction time	Time	4.52	3, 42	0.008*
	Gender	0.43	1, 14	0.524
	Time*Gender	1.18	3, 42	0.331
Stroop task response accuracy	Time	0.47	3, 56	0.703
	Gender	0.43	1, 56	0.517
	Time*Gender	0.3	3, 56	0.828

df: degree of freedom; *: $p < 0.05$ **; $p < 0.001$.

5.4 Discussion

The purpose of this study was to examine whether perceived MF and other psychological characteristics were affected by orienteering competitions. The data indicate that participating in an orienteering competition led to a moderate increase in perceived MF. Importantly, perceived MF remain elevated to a small extent 48 hours following the final competition compared to the pre-competition values. This study also discovered a moderate increase in perceived MF after middle-distance races and a large increase following sprint and long-distance races.

Acute changes in perceived mental fatigue after orienteering competition

Perceived MF moderately increased moderately following the orienteering competition. The combined data analysis found a mean increase of 19.9 AU in perceived MF from pre- to post-orienteering competition, which is similar to previous research with academy to Premier League soccer players (mean difference: 18 to 47 AU)(Abbott et al., 2020; Thompson et al., 2020) and elite netballers (mean difference: 13.7 AU)(Russell et al., 2019). This study utilised a remote data collection method to measure perceived MF, similar to approaches utilised by Russell et al. (2019) and Thompson et al. (2020), but differing from Abbott et al. (2020). However, the similar mean values and mean changes in perceived MF reflect that both remote and in-person data collection methods are effective in capturing changes in perceived MF during competition. Moreover, the mean changes and maximal perceived MF ratings obtained in this study fall within the range reported in previous studies where MF was artificially induced and shown to impair physical performance (see section 2.2.1 and 2.2.2), with mean changes ranging from 8 to 47 AU and maximal mean values between 31 to 68 AU. Importantly, the standard deviation for pre- and post-competition MF ratings was large, indicating substantial individual variation in MF responses. Further discussion regarding the individual variability is provided later in this section. This observation reinforces the understanding of MF as a psychobiological state that does not affect all individuals identically (Van Cutsem et al., 2017; Giboin et al., 2019). Although the precise threshold of MF required to impair athletic performance is not well defined, previous systematic reviews report that increased perceived MF is likely to impair subsequent endurance and decision-making performance (Van Cutsem et al., 2017; Habay et al., 2021; Brown et al., 2019).

This study also examined the changes in perceived MF across orienteering races with different durations (sprint, middle- and long-distance). There were trivial to small differences in the mean changes in perceived MF observed between race types, with the largest increase in perceived MF reported following the sprint event. However, regardless of the race types, the MF ratings remained elevated at MD+1 compared to pre-competition values, with the highest MF ratings observed after the long-distance competition. A small difference in the average change in MF was found between long-distance competition and the other two events when comparing PRE and MD+1. Although both sprint and long-distance competition elicited a large increase in perceived MF from pre- to post-competition, the slower recovery observed following the long-distance competition implies that prolonged exposure to physically and cognitively demanding environments may contribute to sustained MF. This study supports previous findings with the academy to elite soccer players (Abbott et al., 2020; Thompson et al., 2020) and elite netball players (Russell et al., 2019), showing that perceived MF can increase acutely following competition and may remain elevated after the termination of the task. However, this study cannot determine which factor contributes the most to the acute increase in perceived MF during orienteering competition. Despite the greater race duration and distance of the long-distance competition, it did not elicit the highest mean changes in post-competition MF ratings. This supports the findings in Chapter 4 and Giboin et al. (2019) that the extent of MF experienced during orienteering competition may be related to the perceived cognitive and physical effort required to complete the task rather than its duration. Surprisingly, although the sprint races reported the greatest mean change in MF, participants in the long-distance competition had the worst MF ratings at MD+1. This implies that long-distance competition may have a cumulative effect on MF instantly beyond the race itself. These findings are consistent with Smith et al. (2019), who demonstrated that different types of cognitive tasks can elicit MF that varies in duration and recovery.

Acute changes in perceived motivation, physical fatigue, tiredness, stress and mood state after orienteering competition

Our data found that perceived motivation to participate in an upcoming competition decreased to a small extent after orienteering races, while perceived MF moderately increased. This aligns with previous studies showing that mentally fatigued individuals report lower motivation to complete the upcoming activity (Abbott et al., 2020; Russell et al., 2022; Giboin et al., 2019; Martin et al., 2019). According to the proposed mechanism of MF by Martin et al. (2018), the increase of cerebral adenosine in the brain after performing a cognitively demanding task may inhibit dopamine activity in the anterior cingulate cortex, consequently reducing motivation to continue exerting effort. This may explain the observed decline in motivation ratings. Although previous systematic reviews have indicated that motivation is unaffected by MF (Habay et al., 2021; Van Cutsem et al., 2017), strategies such as raising external rewards or listening to self-selected music have been shown to diminish the effects of MF on physical performance (Boksem et al., 2006; Lam et al., 2021). Moreover, monitoring motivation provides additional evidence to determine whether reductions in physical performance caused by MF are attributed to the decrease in motivation (Inzlicht et al., 2013). Importantly, mentally fatigued individuals often report higher ratings of perceived exertion during endurance tasks (Van Cutsem et al., 2017), indicating that perceived exertion may contribute to reduced motivation rather than MF acting as the primary causal factor. Although providing financial incentives has been found to reduce the behavioural impact of MF which encourages participants to engage in a more physically demanding task, this does not necessarily translate into improved physical output as seen in previous research (Brown & Bray, 2017; Harris & Bray, 2021). Furthermore, sport-specific studies have shown that psychological responses can be affected by contextual factors such as the timing of the season or the result of the competitions (Abbott et al., 2020; Russell et al., 2022). While it is plausible that the perceived importance of a race may affect psychological responses, Chapter 4 of this thesis discovered that elite orienteers and practitioners did not consider the perceived importance of competition to be a major factor affecting the extent of MF experienced during orienteering. Future work should consider recording the perceived importance of the competition to validate this observation and to further explore the relationship between motivation and MF in applied sporting contexts.

The ratings of PF, tiredness, BRUMSF and BRUMSC all increased after the orienteering competition even though the extent of these changes varied compared to perceived MF. Conversely, the ratings of stress and BRUMSV decreased following the competition. In agreement with previous investigations on the changes in well-being variables during netball competitions (Russell et al., 2022; Russell et al., 2021) and international orienteering experts' consensus (Chapter 4), this thesis observed the different extent of changes between MF and PF. This demonstrates that MF and PF do not necessarily change simultaneously. When comparing pre- and post-competition in both combined and specific race types, perceived stress ratings decreased after the competition. According to Chapter 4, the higher perceived stress before the competition could be attributed to pre-competition anxiety. While international orienteering experts reported that external stress may contribute to the onset of MF (Chapter 4), stress is not consistently present when athletes are mentally fatigued. Moreover, the mean of stress ratings was higher at MD+1 compared to post sprint, middle- and long-distance races. This may reflect that participants experience higher stress before the competition when perceived MF is low. These findings highlight that perceived stress and perceived MF represent different psychological constructs and should not be used interchangeably.

Previous research has defined MF as an acute increase in subjective ratings of tiredness (Habay et al., 2021; Martin et al., 2018); however, the present study discovered that the magnitude of changes in MF following orienteering competition differed from that of tiredness, as per Russell et al. (2022). This suggests that tiredness, as measured in this study, may not be a consistent symptom of MF. Importantly, the observed differences between MF and other psychological variables such as PF, stress and tiredness reflect that athletes are capable of distinguishing MF from conceptually similar terminology. Additionally, the BRUMS mood state measured before and after competition showed a decrease in vigour and an increase in fatigue scores, aligning with previous research using laboratory-based MF protocols (Van Cutsem et al., 2017). Chapter 4 highlighted the relevance of confusion as a symptom of MF, as the international orienteering experts agreed orienteers may experience confusion when they are mentally fatigued. Our data reported a small increase in BRUMSC following the competition. When examining the magnitude of changes across race types, the ratings of tiredness, BRUMSV, BRUMSF and BRUMSC increased progressively, with the long-distance competition eliciting the largest changes except for the MF and motivation ratings. The changes in the remaining outcome variables (MF, motivation, PF stress) appeared unaffected by the race types, with a trivial to small difference between race types. Taken together, we cannot rule out the possibility that these variables are interlinked but providing a clear distinction between variables was beyond the scope of this study. The present study found that orienteering competition can elicit small to very large negative changes in MF and other psychological responses, emphasising MF should be monitored separately.

Changes in subjective outcome variables at 24- and 48-hours after the final competition

As discussed earlier, the extent of changes in perceived MF and other outcome variables showed trivial to moderate differences at MD+1 across sprint, middle- and long-distance competition when compared to pre-competition value. However, it is important to note that this study recorded at least four different racing schedules, ranging from one-day to four-day events, with variations in race order among participants. Due to the small sample size and inconsistency in the racing schedule, this study cannot provide a comprehensive conclusion on whether the race order of the event influenced the results.

The comparison between the last day of the post-competition value and 48POST revealed that, except for BRUMS confusion ratings, all variables did not recover to the PRE1 value by 48POST. These findings align with previous research reporting that MF, stress and mood can remain elevated for 24- to 48 hours after a soccer match (Abbott et al., 2018; Abbott et al., 2020; Thompson et al., 2020). A study of 11 under 23 elite football players demonstrated that the impaired subjective ratings of stress and mood could be sustained up to 72 hours post-competition especially when matches were played away from home or resulted in a loss (Abbott et al., 2018). Collectively, this indicates that psychological responses induced by orienteering competitions can remain impaired for up to 48 hours. Although a progressive improvement in most variables was found over the two-day recovery period, the majority of variables were still negatively impacted 48 hours post-competition. This implies that recovery from competition may require more than 48 hours, and future research should consider a longer observation period to better understand the recovery timeline. By extending the monitoring period, it may provide insight into how athletes' well-being and performance change post-competition. The present study supports that MF can be acutely induced and accumulate at MD+1. Furthermore, the cumulative effect of elevated MF requires further investigation. Previous research involving 63 Olympic-level open and closed-skill sports athletes found that elevated MF ratings may not significantly affect the ratings of perceived exertion during a single training session, but the failure to recover from the increased MF can affect the total perceived exertion across a training week (Coyne et al., 2021). Therefore, based on our findings, the MF and other psychological responses affected by the competitions require at least 48 hours to recover to pre-competition values. This reflects the importance of incorporating appropriate recovery strategies when planning training and competition to optimise athlete readiness and performance in orienteering.

It is also important to consider the potential influence of perceived sleep quality on perceived MF and other well-being variables. Our findings reported that sleep quality ratings were lower before the final day of competition, as well as 24POST and 48POST compared to the pre-competition levels. One plausible explanation for this decline is the travel burden associated with the orienteering competitions, many of which were held in rural locations, requiring prolonged travel either on the day of or the day prior to the competition. Previous research has reported that long-haul travel to the competition including travel to away match is perceived as mentally fatiguing (Abbott et al., 2020; Thompson et al., 2020; Thompson et al., 2021) and can negatively affect sleep quality (Fullagar et al., 2016). Unlike team sports, orienteering does not have a home or away setting, and the nature of the sport requires athletes to frequently travel and adapt to unfamiliar environments and terrain. This experience across levels of orienteers may contribute to compromised sleep and increased fatigue before and following competition. As such, the role of travel and sleep quality should not be overlooked.

It remains unclear whether the elevated outcome variables at 24POST and 48POST were primarily influenced by low sleep quality or fatigue from competitions or the demands of long-haul travel home. Fullagar et al. (2016) found that reductions in sleep quality and perceived recovery are associated with the time of the day, but our study did not record the timing of the competition, limiting the ability to evaluate these changes. The current study indicates that attention should not only be given to pre- and post-competition changes but also to the recovery period afterwards in order to enhance the recovery management of orienteers. This information is particularly important for orienteering practitioners as orienteering competitions are mostly held in rural areas, where lengthy travel is unavoidable. Additionally, none of the participants were full-time athletes and the workload of their occupations could have influenced the changes in MF and psychological responses outside of competition. As reported in Chapter 4 and Thompson et al. (2020), non-orienteering challenges such as work and education have been perceived to contribute to perceived MF. Further research should consider investigating the impact of these extraneous variables to improve understanding of MF in orienteering. According to Figures 5.3 and 5.4, it demonstrate that the 95%CI for the mean MF ratings at 24POST and 48POST overlapped with those of the pre-competition values. While this may raise concerns about the accuracy of the findings, section 2.5.2.4 reports the potential limitations of using the mean results derived from the VAS scores, which may lead to interpretation errors. However, the large and overlapped SD observed is likely reflecting the subjective nature of MF and individual variability in perception, rather than a methodological error. Further discussion on the limitations of the socring methodology and the statistical analysis can be found in sections 7.3.1.5 to 7.3.1.7.

Reaction time and response accuracy during Stroop task

The Stroop task has been widely utilised to induce MF (Brown et al., 2020; Giboin & Wolff, 2019; Van Cutsem et al., 2017) and to measure the impact of MF on cognitive performance

(Fortes et al., 2020; Fortes et al., 2021). However, despite increases in MF, our data did not report impairment in Stroop task performance either immediately post-competition or over the 48-hour recovery period. This contrasts with previous research in which significantly slower reaction time and higher perceived MF were found in 25 professional swimmers (Fortes et al., 2020) and 25 well-trained boxers (Fortes et al., 2021) after a 30-minute MF intervention using a similar Stroop task for measurement. To elaborate, the current findings investigated the perceptual changes before and after an actual orienteering competition rather than using an artificial MF intervention. These methodological discrepancies make it challenging to provide a direct comparison of the effectiveness of utilising the Stroop task to detect MF. One plausible explanation for the absence of impairment is that the cognitive load imposed by the Stroop task may not sufficiently challenge orienteers, who are used to making rapid and precise decision-making using a map and compass in dynamic and visually complex environments. Previous research also indicates that well-trained individuals may have superior inhibitory control (Cona et al., 2015) and require less cognitive effort to process simple visual stimuli (Borragán et al., 2017), potentially reducing the sensitivity of the Stroop task for the orienteering population. Although familiarisation trials were included to improve test reliability, they do not guarantee task sensitivity or ecological validity, especially the Stroop task may not adequately replicate the specific cognitive demands as discussed in section 2.4.1.1. To conclude, the findings suggest that the Stoop task may not be an appropriate tool for assessing the effects of MF in trained orienteers. Future research should consider using sport-specific taskd that better replicate the decision-making and visual-spatial demands of orienteering to accurately evaluate the effect of MF in this population.

Physical demand of the orienteering competition

A previous systematic review summarizing the physiological demands of orienteering competitions provides an overview of the energy requirements of orienteering (Batista et al., 2020); However, it was unable to differentiate between race types due to a lack of evidence. Although the sample size in the current study was small, it covered three different types of orienteering races and recruited national-level orienteers with similar ages, thereby overcoming a key limitation of previous research that used participants with varying ages (Larsson et al., 2002; Smekal et al., 2003). The present study measured the running speed and found that sprint required the fastest running speed, with a moderate to large difference compared to middle- and long-distance competitions. However, the recorded HR were similar and the small difference in running speed between middle- and long-distance competitions reflects that the overall physical demands of these two race formats may be similar.

Perceived causes of mental fatigue during orienteering competition

The top three perceived causes of MF identified in the present study were "physical demand of the race", "stress from the race and/or mistakes", and "technical demand and/or the difficulty of the race". Similar themes have been identified in previous research exploring the descriptors of MF among academy elite football players, elite netball players and international orienteering experts (Thompson et al., 2021; Russell et al., 2019; Lam et al., 2023). These include "difficulty in reacting to mistakes" (Thompson et al., 2020), "inconsistency of the competitive environment" (Russell et al., 2019), "internal stress to succeed" (Thompson et al., 2021), "external pressures/ stress" and "complexity of the task" (Chapter 4), reflecting similarities with our findings. Interestingly, while the experts in Chapter 4 did not fully agree that the physical demands of the race directly caused MF, they did agree that being physically fatigued may intensify the perception of MF. This aligns with the current finding that physical demand is perceived to be a primary factor contributing to MF during orienteering. However, the influence of physical exertion on the development of MF remains uncertain. This suggests the potential for misunderstanding when discussing the relationship between MF and PF. Therefore, it is important to clearly define the concept of MF to athletes and practitioners to increase the accuracy of research on this topic.

Individual variability in the responses

The results underscore the importance of incorporating random intercepts to accurately model individual differences across all outcome variables, demonstrating substantial variability in individual responses to orienteering competitions. The significant improvement in model fit when using random intercept models aligns with previous research on the individualized experience of fatigue (Russell et al., 2019; Russell et al., 2022), indicating that individuals respond differently to orienteering competition. The wide range of random intercept estimates for each participant for all outcome variables reflects considerable individual variation relative to the overall mean. This implies that relying solely on overall means may be inadequate for understanding the competition-induced effects on MF and other psychological responses. Despite the observed high inter-individual variability, the inclusion of random slopes for time and/or gender did not significantly improve model fit, reinforcing that random intercept models provide a more precise reflection of participants' experiences during and after the orienteering competition.

The results of the random intercept model after accounting for individual variability revealed a significant effect of time on perceived MF, PF, motivation, tiredness, BRUMSF and BRUMSC. The Bonferroni post-hoc analyses showed significant increases in the ratings of perceived MF, PF, tiredness, BRUMSF, and BRUMSC after the orienteering competition, while motivation ratings declined. These findings align with the effects of MF reported in section 2.5.2 and other observational studies (Russell et al., 2022), where MF occurs with impairments in other psychological responses. Although a significant interaction between time and gender was observed in BRUMSV, with female participants showing a greater decline from pre- to post-competition, the post-hoc analyses did not report significant differences between male and female orienteers. A similar observation was observed when comparing PRE to MD+1 in sprint and long-distance races, where female participants reported significant impairments and higher ratings in stress than male participants. These findings suggest potential gender-related differences in emotional responses; however, they remain inconclusive since recent review highlight gender does not affect susceptibility to MF (Habay et al., 2023). It is important to note that the imbalanced gender sample and variability in race order, race type, and competition duration limit the ability to draw a meaningful conclusion regarding gender-related differences in the current study. Future studies should aim to include more balanced samples and controlled competition conditions to better clarify the potential effects of gender on MF. While our findings suggest gender may be relevant in some contexts, it did not play a critical role in the overall pre-, post-, and recovery patterns observed.

Despite the significant increase in perceived MF, no significant changes were observed in the Stroop task reaction time and response accuracy. This finding contrasts with previous findings presented in sections 2.5.1.1.2 and 2.5.1.2, where MF has been associated with impairments in cognitive performance. The stable executive function observed throughout the orienteering competition suggests that the Stroop task may lack sensitivity in detecting MF-related cognitive changes in well-trained orienteers. This limitation reinforces the need for future research to explore alternative cognitive tasks that accurately replicate the executive function and decision-making demands of orienteering in order to assess cognitive performance effectively.

When comparing the recovery phases to the ratings before the first day of the orienteering competition, significant time effects were observed for most outcome variables, except for stress ratings and Stroop task response accuracy. The Bonferroni post-hoc analyses showed that MF, PF, tiredness, and BRUMSF ratings remained significantly higher at 24POST, while motivation ratings were significantly lower compared to PRE1. Conversely, the Stroop task reaction time was significantly faster at 48POST, suggesting a potential cognitive adaptation following the orienteering competition. The delayed recovery of perceived MF aligns with similar observational research with elite athletes (Thompson et al., 2020; Abbott et al., 2020; Russell et al., 2019), which also reported that MF can remain elevated after the termination of competition. These findings highlight the importance of identifying effective recovery strategies to optimise psychological recovery following competition.

Although this study employed mixed-effects modelling, including random intercept and random intercept plus random slope models with time and/or gender to account for individual variability, the exclusion of race type, competition duration, and race order due to convergence issues limits the generalisability of the findings. Future studies should consider larger sample sizes to better accommodate these variables and enable more robust statistical modelling of these effects. In conclusion, this study highlights the significant psychological demands induced by orienteering competition, with perceived MF persisting beyond the completion of the event. The delayed recovery observed during the post-competition phase suggests the need for future research to explore individualized recovery interventions to mitigate prolonged fatigue effects and optimise post-competition readiness.

5.5 Conclusions

This study presents the first strong evidence that participating in sprint, middle-distance or long-distance orienteering competition leads to an acute increase in an orienteer's subjective ratings of MF, PF, tiredness, BRUMSF, and BRUMSC along with decreases in the ratings of motivation, stress, and BRUMSV. This study also observed that orienteers who competed in long-distance competitions had the worst ratings across all outcome variables both immediately after and the day after the competition, compared to those in sprint or middle-distance races. However, the negative effects induced by competition were found across all race types, with most psychological responses remaining impaired 24 hours post-competition, except for the stress and BRUMSC ratings in long-distance orienteering. With the exception of stress and

BRUMSC ratings, the majority of variables did not recover to pre-competition values 48 hours after the completion of the final orienteering competition.

Chapter 6: Exploring the Impact of an Orienteering Training Camp on Perceived Mental Fatigue, Physical Fatigue and Mood State in a National Junior Squad of Orienteers

Part of the findings from this chapter were presented at the 6th International Congress on Soldier's Physical Performance 2023 (Poster presentation).

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6.1 Introduction

As reported in Chapter 4, international orienteering experts acknowledged that MF arises during orienteering competitions and this was successfully demonstrated in Chapter 5. However, the experts emphasised that the MF experienced during training differs from that experienced during competition, highlighting that the unique psychological demands of competition cannot be replicated in training. In support of this, a two-year longitudinal study with elite netball players reported substantially lower perceived MF ratings during competition than those reported during training camps and competition preparation periods (Russell et al., 2021). Coyne et al. (2021) discovered that while the acute changes in MF within a single training session may not significantly affect elite team and individual sport athletes' perceived exertion during competition preparation, cumulative MF over the course of a training week may significantly affect the overall internal training load. Similarly, an observational study with elite netballers reported significantly higher perceived MF during the latter weeks of the 16-week pre-season training (Russell et al., 2022). These findings show that perceived MF is not limited to competitions but can also build up throughout training periods.

Whilst Chapter 5 reported impairements in subjective ratings of MF, PF and mood state following the orienteering competitions, additional research is required to determine whether similar psychological responses are elicited during orienteering training. This would help validate the consensus made by orienteering experts in Chapter 4 and enhance the development of appropriate strategies for the preparation and monitoring of orienteering athletes across both training and competition environments.

Therefore, the purpose of this study was to investigate how perceived MF, mood, and other psychological responses changed during an orienteering training camp including the national orienteering squad. Similar to previous research with elite netballers during training and competition (Russell et al., 2022), this study did not formulate a hypothesis to allow greater flexibility in exploring potential differences in assessing perceived MF and other psychological responses throughout the orienteering training camp.

Research Question: Do junior orienteers experience MF during an orienteering training camp?

6.2 Methodology

Standardised conceptualization of mental fatigue among participants

In line with Chapter 5, this study used the same definition of MF provided by international orienteering experts in Chapter 4. MF was defined as an inability to maintain concentration and process information for decision-making efficiently and effectively following a prolonged period of cognitively demanding activity (Lam et al., 2023).

Experimental design

An observational study design with repeated measures was utilised to observe the changes in perceived MF and other psychological variables during a 4-day simulated orienteering competition preparation camp.

Participants

Eleven British national junior orienteers (5 males and 6 females, aged 15-17 years, height 1.69 ± 0.07m, body mass 59.9 ± 5.2kg, 8.7 ± 3.8 years competitive experience; England: n = 7 and Scotland: n = 4) voluntarily participated in the study. All participants were full-time students on spring break during the research period. One participant did not complete the survey on the second or third day of the camp due to technical difficulties; however, their data from the remaining days were included in the analysis. All participants met the inclusion criteria presented in section 3.2 and were categorised as Tier 3 highly trained individuals (McKay et al., 2022). Following institutional ethical approval, written informed consent and parental consent were received from all participants before taking part. A sample size of 17 was initially estimated to achieve an average target margin of error of 0.4 using $\rho = 0.70$ in order to reach the desired degree of precision, based on the precision planning for a paired-sample design utilising the Exploratory Software for Confidence Intervals (Cumming, 2012). With the final sample size of 11 participants in this study, the calculated margin of error for a 95% confidence interval was 0.55.

Simulated orienteering competition training camp

The four-day orienteering training camp was designed by coaches from the British Orienteering Talent Squad to simulate competitive conditions and prepare orienteers for upcoming races. All participants arrived one day before the start of the training camp and stayed at the same accommodations throughout the camp. The primary objective of the camp was to replicate orienteering competition conditions including sprint, relay, middle- and long-distance races. The details of the camp schedule are displayed in Table 6.1. All participants followed the same training programme, which included approximately six hours of scheduled training sessions per day, along with an additional hour for pre-race preparation and post-race analysis. According to Table 6.1, two simulated races were held on days 1 and 3 of the training camp. In addition to sprint, middle-distance, and long-distance orienteering competition formats, the training camp also incorporated orienteering relay-specific training on days 3 and 4. The relay format involved teams consisting of three members, with each participant assigned to the 1st leg, 2nd leg, or 3rd leg. For training purposes, all participants ran the 1st leg on day 4, whereas on day 3, participants were assigned to either the 2nd leg or 3rd leg. The relay race began with a mass start for the 1st leg, with all orienteers starting from the same location. The handover for the 2nd and 3rd leg took place at the same designated spot. There are three separate courses (A, B & C) with different section orders for each team, such as C-A-B, B-A-C or A-C-B. Although the course sequences varied, the total distance and technical difficulty were comparable across all team members.

Table 6.1 The structure of the 4-day simulated orienteering competition training camp.

Day 1	
Time	Activity
0800-0930	Breakfast
0930-1030	Middle-distance race preparation
1030-1430	Travel to race venue
1500-1800*	Middle-distance race
1800-1930	Dinner
1930-2230	Post-race Analysis and Sprint race
Day 2	
0800-0930	Breakfast
0930-1030	Long-distance race preparation
1030-1130	Travel to race venue
1130-1800*	Long-distance race
1800-1930	Dinner
1930	Post-race analysis
Day 3	
0800-0930	Breakfast
0930-1030	Relay race preparation
1030-1130	Travel to race venue
1130-1500*	2nd or 3rd leg relay practice
1500-1700	Night orienteering preparation
1700-1800	Travel to race venue
1800-2000*	Night orienteering
2000	Dinner
Day 4	
0800-0930	Breakfast
0930-1000	Relay race preparation
1000-1045	Travel to race venue
1045-1230*	1st leg mass start relay
1230	Depart from the camp

*: The time included briefing, general preparation and the actual running of the race.

Procedure

An online self-report questionnaire was completed using the Qualtrics XM Platform (USA). Participants completed the self-report measures daily within 30 minutes of waking (PRE1-4) and within 30 minutes of completing each training session (POST1-4) across the four training days. This approach is identical to Chapter 5 and previous research (Russell et al., 2022). Additionally, participants completed the same self-report measures 24- (24POST) and 48-hour (48POST) following the training camp in order to assess post-camp recovery. All self-report measures were completed privately on participants' personal electronic devices such as laptops, smartphones or tablets to reduce the response bias (Russell et al., 2022).

Online Self-report Measures

The daily self-report measurements were identical to section 5.2. The schematic timeline of the measurements is detailed in Figure 6.1. To ensure consistency with Chapter 5, all participants completed a familiarisation trial one week before the experiment using the same self-report tools. The reliability and validity of 100mm VAS and the BRUMS were highlighted and discussed in sections 3.3.2.2 and 3.3.2.3. The questions and descriptors for the variables measured via 100mm VAS were identical to Chapter 5, as displayed in section 3.3.2.2. Given the findings in Chapter 5 that the 30-word congruent and incongruent Stroop task did not demonstrate sensitivity for detecting MF among orienteers in Chapter 5, this study excluded this objective measure of MF to prevent any potential confusion.

1. MF 2. Motivation 3. Sleep quality 4. PF 5. Stress 6. Tiredness 7. BRUMS	1. MF 2. Motivation 3. PF 4. Stress 5. Tiredness 6. BRUMS 7. Perceived causes of MF	1. MF 2. Motivation 3. Sleep quality 4. PF 5. Stress 6. Tiredness 7. BRUMS	1. MF 2. Motivation 3. Sleep quality 4. PF 5. Stress 6. Tiredness 7. BRUMS
Day 1-4 pre-training	Day 1-4 post-training	24-hours after the training camp	48-hours after the training camp

Figure 6.1 The time of the measurements during orienteering training camp.

Statistical Analysis

In addition to the statistical analysis outlined in section 3.4, specific data analysis was conducted for this study. The magnitude of changes in paired comparisons for the ratings of perceived MF, motivation, sleep, PF, stress, tiredness, and BRUMS were analysed using ES with 95% CI. To examine the overall influence of the simulated orienteering competition training camp, subjective outcome variables recorded from day 1 to day 4 were initially combined to assess the pre- and post-orienteering training differences. The magnitudes of changes in all outcome variables were also analysed to compare the differences across three post-training time points: immediately after the final training session (POST4), 24 hours (24POST), and 48 hours (48POST) post-training camp. Additionally, the athletes' perceived causes of MF during the orienteering training camp were analysed using a summative content analysis as mentioned in section 3.4.2.

In the supplementary analysis, LMM were employed to investigate the ratings of perceived MF, motivation, PF, stress, tiredness, and BRUMS. This analysis aimed to explore individual differences and random effects across participants throughout the 4-day simulated orienteering competition training camp, as described in section 3.4.2. Participants were included as random intercept factors, while gender and time of measurement were included as fixed factors. The model selection criteria were outlined in section 3.4.2. The structure of data presentation followed the earlier analysis: the first part examined the changes between pre- and post-orienteering training camp, and the second part focused on the recovery phase, specifically from POST4 to 48POST, as well as comparisons to the values recorded before the first training session (PRE1).

6.3 Results

Pre and post orienteering training (42 responses)

This analysis presented all pre- to post- training pairwise comparisons for the outcome variables recorded from day 1 to day 4 of the training camp. The mean changes in these outcome variables for all participants are presented in Figure 6.2. There was a moderate increase in the subjective ratings of MF, PF and BRUMSF, as well as a small increase in tiredness and BRUMSC following orienteering training. Conversely, BRUMSV demonstrated a small decrease, while motivation and stress ratings reported a trivial decline following orienteering training.

Variables	PRE	POST	Mean Difference [95%CI]	Effect size [95%CI]
Mental Fatigue	37.3 ± 23.1	59.8 ± 19.3	22.5 [15.6 , 29.5]	1.06 [0.66 , 1.45]
Motivation	55.2 ± 27.4	54.1 ± 24.6	−1.1 [-9.7 , 7.5]	−0.04 [-0.36 , 0.28]
Physical Fatigue	50.2 ± 22.8	73 ± 19.6	22.9 [16.3 , 29.4]	1.07 [0.69 , 1.45]
Stress	31.1 ± 20	29.5 ± 16.6	−1.6 [-9.2 , 6]	−0.09 [-0.49 , 0.32]
Tiredness	51 ± 21.8	60.3 ± 21.2	9.3 [3.6 , 15]	0.43 [0.16 , 0.7]
BRUMS Vigour	7.5 ± 3.6	5.6 ± 3.2	−1.9 [-2.9 , -0.9]	−0.55 [-0.85 , -0.25]
BRUMS Fatigue	7.4 ± 4.1	10.2 ± 3.6	2.8 [1.7 , 3.9]	0.74 [0.4 , 1.1]
BRUMS Confusion	1.4 ± 2	2.3 ± 2.5	0.9 [0 , 1.8]	0.4 [0.02 , 0.78]

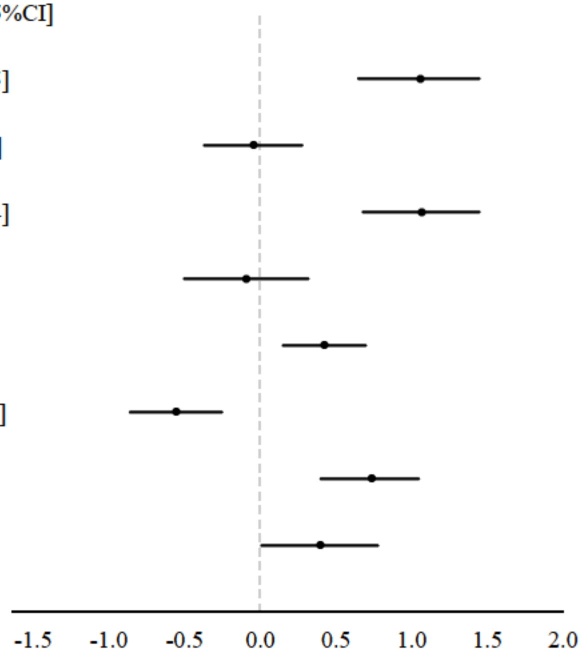
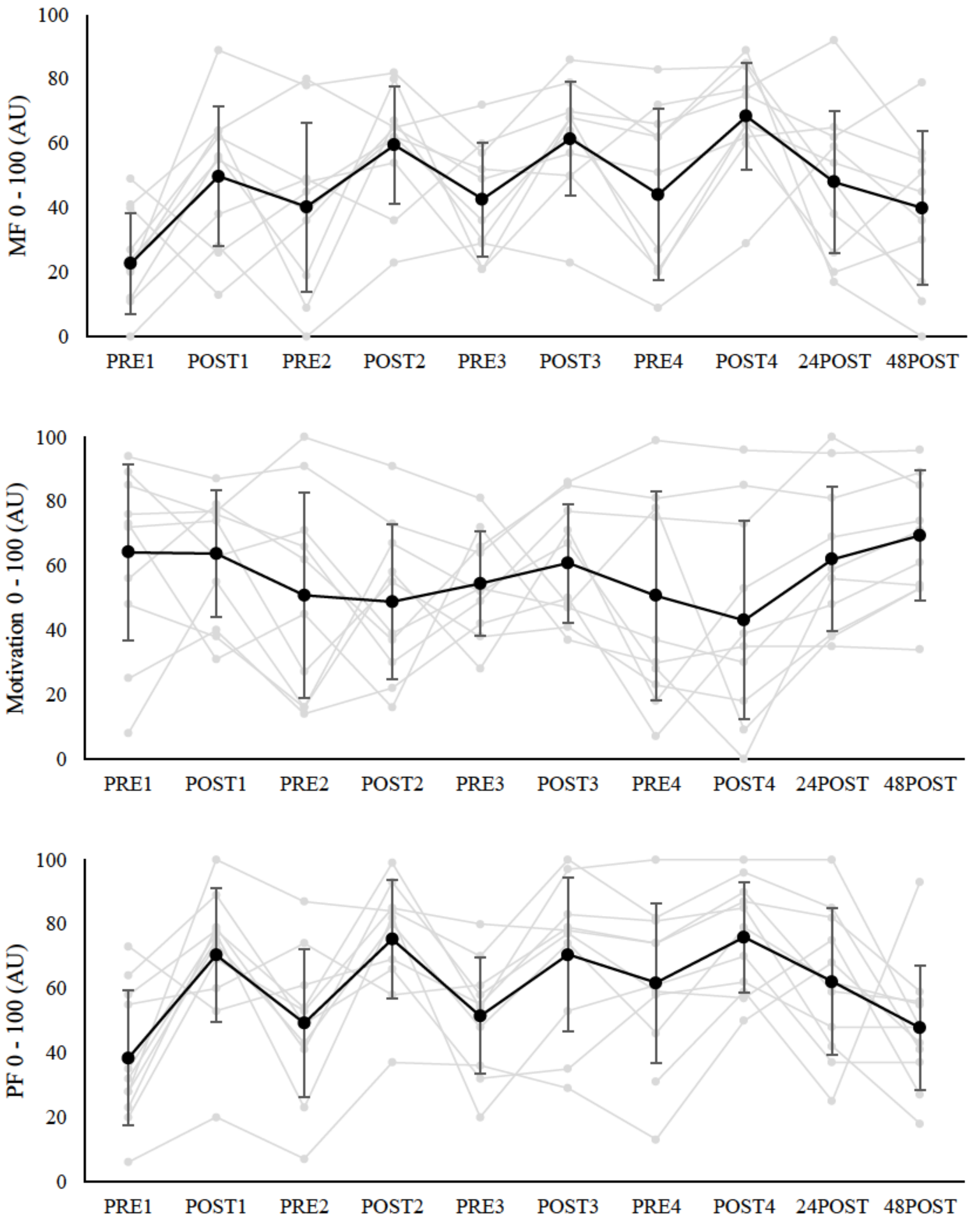


Figure 6.2 The magnitude of changes in all outcome variables before and after an orienteering training. Data has been combined from all participants (42 responses).

Pre- to post-training changes across consecutive days

Figure 6.3 shows the changes in survey responses across the four consecutive days of training, while Table 6.2 displays the extent of changes between training days for ten participants. One participant did not complete the surveys on day 2 and day 3 due to technical difficulties. According to Figure 6.3, the pre-training ratings of perceived MF, PF, and BRUMSF progressively increased over the four training days, with a moderate increase observed in MF (PRE1 vs PRE2: ES = 0.74 [-0.02 , 1.46]) and PF (PRE3 vs PRE4: ES = 0.64 [-0.08 , 1.32]). However, the other outcome variables did not demonstrate a consistent increasing or decreasing trend during the training camp. Regarding post-orienteering training ratings, only the rating of MF demonstrated a progressive increase with a trivial to small ES (POST1 vs POST2: ES = 0.49 [-0.18 , 1.13]; POST2 vs POST3: ES = 0.11 [-0.37 , 0.58]; and POST3 vs POST4: ES = 0.44 [0.05 , 0.82]). The remaining outcome variables did not report a consistent pattern of change following training sessions.

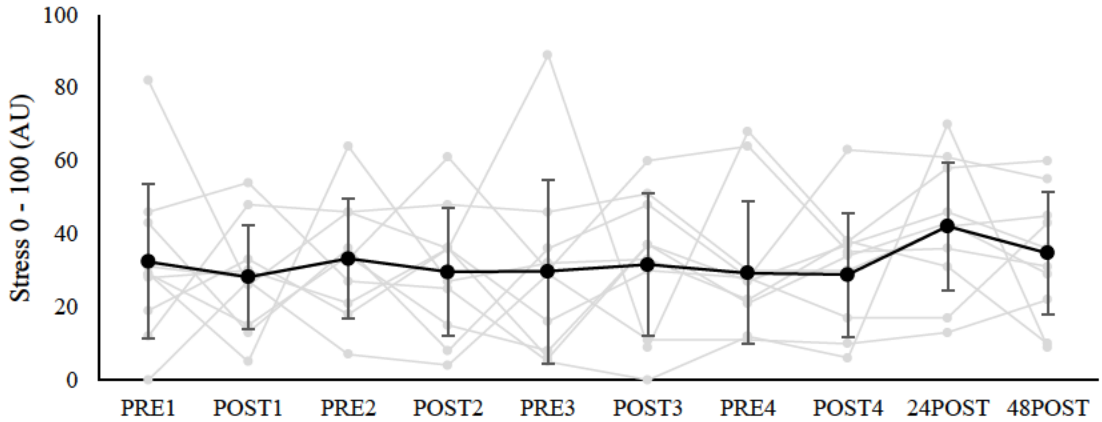


A.

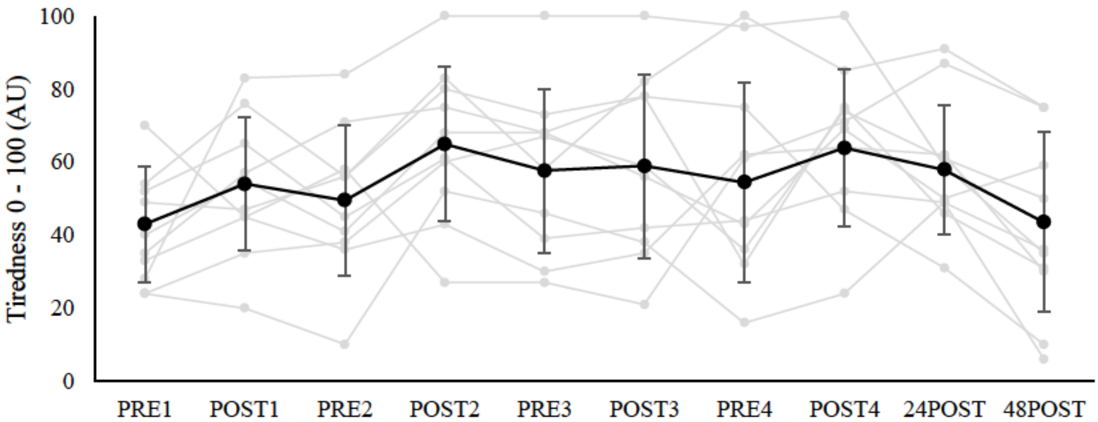
B.

C.

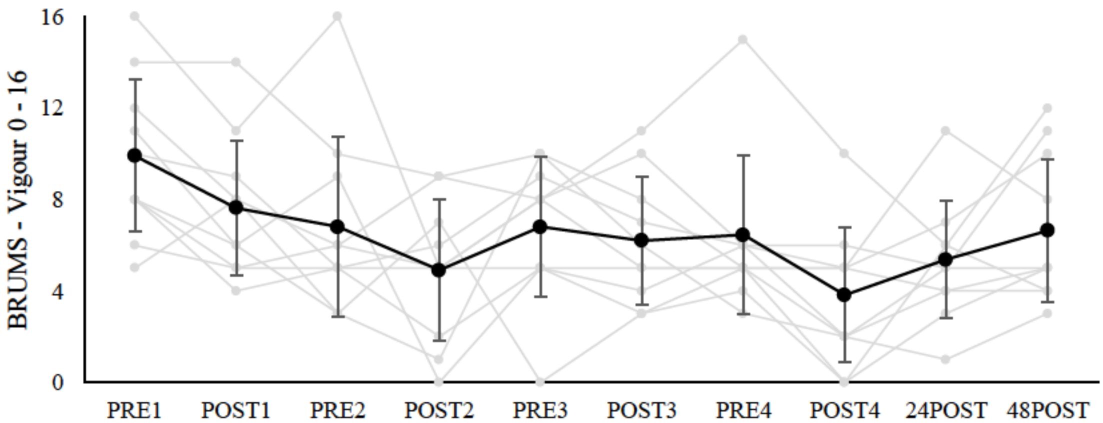
Figure 6.3 The changes in MF (A), motivation (B), PF (C), stress (D), tiredness (E), BRUMSV (F), BRUMSF (G), BRUMSC (H) and perceived sleep quality (I). from day 1 to 48 hours after orienteering training camp. The black circles represent mean value with 95%CI and the grey lines present the individual ratings of 10 participants. The responses from ten participants was utilised for time points PRE2, PRE3, POST2, and POST3. All participants (n = 11) were included for the other time points.



D.

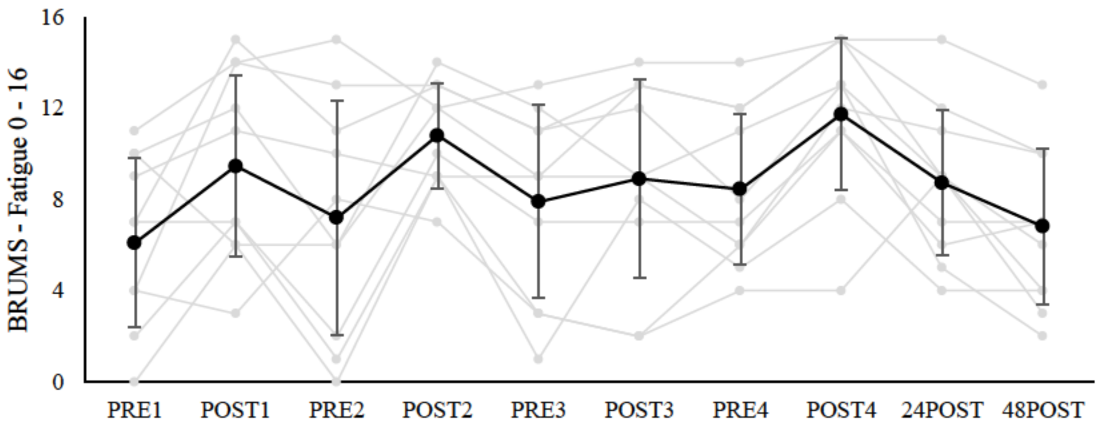


E.

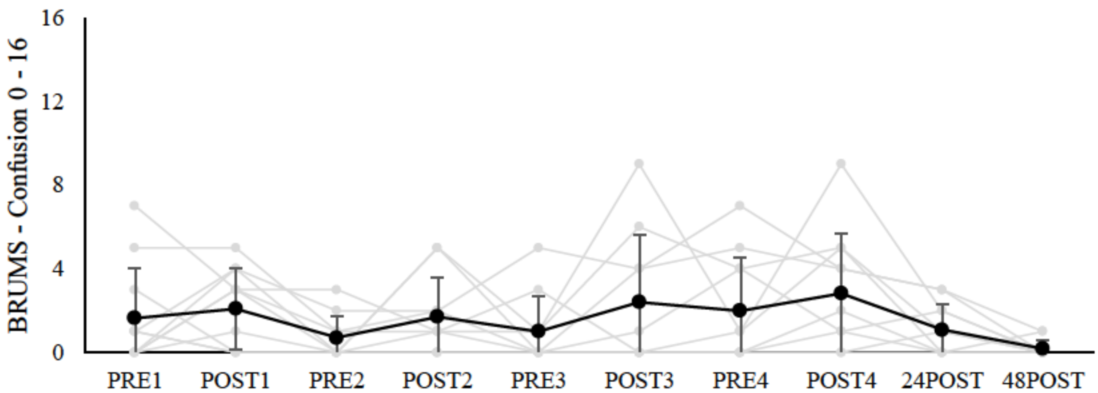


F.

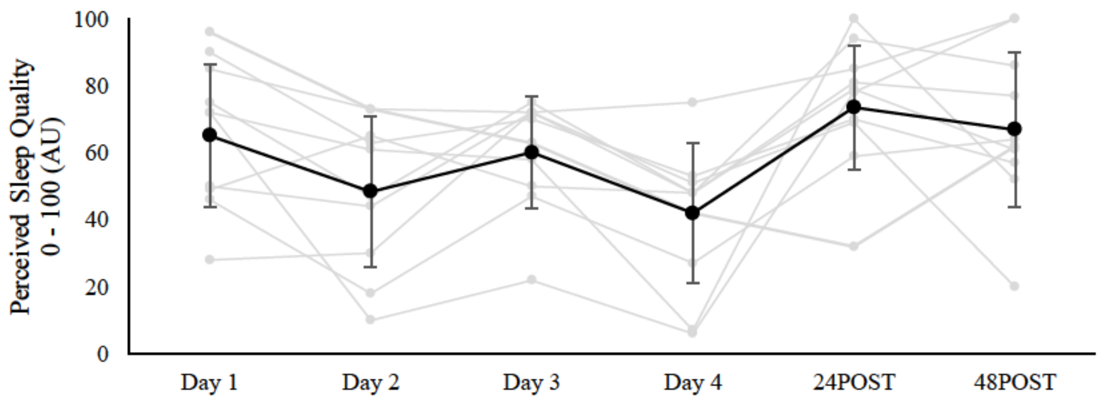
Figure 6.3 Continued.



G.



H.



I.

Figure 6.3 Continued.

Table 6.2 The comparison of the magnitude of changes in all outcome variables before and immediately after training from 10 participants.

Variables	PRE to POST change				
	Mean difference [95%CI]	Effect size [95%CI]	Changes between days (Effect size [95%CI])		
			vs Day 2	vs Day 3	vs Day 4
Mental Fatigue 0 – 100 AU					
Day 1	25 [4 , 46]	1.29 [0.16 , 2.37]§	-0.21 [-1.06 , 0.66]	-0.26 [-0.84 , 0.34]	-0.13 [-0.89 , 0.64]
Day 2	19.3 [0.8 , 37.8]	0.85 [0.03 , 1.64]*		-0.02 [-0.64 , 0.6]	0.13 [-0.56 , 0.81]
Day 3	18.8 [6.1 , 31.5]	1.06 [0.26 , 1.83]*			0.19 [-0.42 , 0.79]
Day 4	22 [10.8 , 33.2]	1 [0.35 , 1.62]*			
Motivation 0 – 100 AU					
Day 1	-0.6 [-18.5 , 17.3]	-0.03 [-0.66 , 0.61]	-0.05 [-0.64 , 0.55]	0.28 [-0.44 , 0.98]	-0.12 [-1.07 , 0.84]
Day 2	-2 [-25.1 , 21.1]	-0.07 [-0.78 , 0.64]		0.29 [-0.45 , 1.01]	-0.06 [-0.89 , 0.78]
Day 3	6.4 [-11.6 , 24.4]	0.37 [-0.56 , 1.27]			-0.37 [-0.98 , 0.25]
Day 4	-3.8 [-24.8 , 17.2]	-0.12 [-0.68 , 0.45]			
Physical Fatigue 0 – 100 AU					
Day 1	30.9 [11.4 , 50.4]	1.4 [0.38 , 2.38]§	-0.19 [-0.91 , 0.55]	-0.53 [-1.4 , 0.38]	-0.85 [-1.78 , 0.12]*
Day 2	26.1 [8.7 , 43.5]	1.25 [0.31 , 2.15]§		-0.34 [-1.17 , 0.51]	-0.68 [-1.64 , 0.31]*
Day 3	19.1 [7.4 , 30.8]	0.9 [0.26 , 1.51]*			-0.43 [-1.47 , 0.64]
Day 4	12.8 [3.4 , 22.2]	0.62 [0.12 , 1.09]*			
Stress 0 – 100 AU					
Day 1	-4 [-23.9 , 15.9]	-0.21 [-1.12 , 0.71]	0.02 [-0.62 , 0.65]	0.19 [-0.47 , 0.84]	0.15 [-0.72 , 1.01]
Day 2	-3.6 [-18.4 , 11.2]	-0.21 [-0.97 , 0.55]		0.2 [-0.58 , 0.97]	0.16 [-0.96 , 1.28]
Day 3	1.9 [-21.7 , 25.5]	0.08 [-0.83 , 1]			-0.08 [-0.77 , 0.61]
Day 4	-0.3 [-14.7 , 14.1]	-0.02 [-0.71 , 0.67]			
Tiredness 0 – 100 AU					
Day 1	11.9 [-3 , 26.8]	0.7 [-0.14 , 1.5]*	0.17 [-0.56 , 0.9]	-0.64 [-1.53 , 0.27]*	-0.11 [-0.98 , 0.76]
Day 2	15.4 [1.4 , 29.4]	0.74 [0.05 , 1.4]*		-0.89 [-1.83 , 0.09]*	-0.28 [-1.23 , 0.68]
Day 3	1.3 [-6.3 , 8.9]	0.06 [-0.23 , 0.33]			0.48 [-0.57 , 1.5]
Day 4	9.5 [-6.2 , 25.2]	0.39 [-0.2 , 0.95]			

* a moderate difference (ES ≥ 0.6); § a large difference (ES ≥ 1.2).

Table 6.2 Continued.

Variables	PRE vs POST				
	Mean difference [95%CI]	Effect size [95%CI]	Changes between days (Effect size [95%CI])		
			vs Day 2	vs Day 3	vs Day 4
BRUMS Vigour 0 – 16					
Day 1	-2.2 [-4 , -0.4]	-0.67 [-1.22 , -0.09]*	0.08 [-0.64 , 0.79]	0.64 [-0.47 , 1.71]*	-0.04 [-0.82 , 0.74]
Day 2	-1.9 [-5.3 , 1.5]	-0.54 [-1.4 , 0.35]		0.34 [-0.6 , 1.26]	-0.11 [-0.79 , 0.58]
Day 3	-0.6 [-2.4 , 1.2]	-0.2 [-0.74 , 0.34]			-0.73 [-1.87 , 0.44]*
Day 4	-2.3 [-3.8 , -0.8]	-0.72 [-1.23 , -0.18]*			
BRUMS Fatigue 0 – 16					
Day 1	3.1 [0.1 , 6.1]	0.78 [0.01 , 1.51]*	0.11 [-0.86 , 1.08]	-0.58 [-1.43 , 0.3]	0.03 [-0.99 , 1.05]
Day 2	3.6 [0.3 , 6.9]	0.9 [0.05 , 1.72]*		-0.68 [-1.52 , 0.2]*	-0.11 [-1.1 , 0.88]
Day 3	1 [-1 , 3]	0.23 [-0.2 , 0.65]			0.92 [-0.06 , 1.85]*
Day 4	3.2 [1.9 , 4.5]	0.92 [0.38 , 1.44]*			
BRUMS – Confusion 0 – 16					
Day 1	0.5 [-1.5 , 2.5]	0.23 [-0.57 , 1.01]	0.2 [-0.76 , 1.15]	0.3 [-0.79 , 1.37]	0.13 [-0.93 , 1.18]
Day 2	1 [-0.6 , 2.6]	0.65 [-0.33 , 1.6]*		0.14 [-0.27 , 0.55]	-0.04 [-0.86 , 0.79]
Day 3	1.4 [-0.9 , 3.7]	0.55 [-0.3 , 1.36]			-0.15 [-0.88 , 0.58]
Day 4	0.9 [-1.4 , 3.2]	0.33 [-0.44 , 1.09]			

* a moderate difference (ES ≥ 0.6); § a large difference (ES ≥ 1.2).

Perceived sleep quality during and after orienteering training camp

The perceived sleep quality was assessed daily within 30 minutes of waking. As shown in Figure 6.3, the perceived sleep quality during the orienteering training camp is labelled as day 1-4 rather than PRE1-4 and POST1-4. Perceived sleep quality moderately declined from day 1 to day 2 (ES = -0.8 [-1.48 , -1]), followed by a small increase from day 2 to day 3 (ES = 0.59 [-0.08 , 1.23]). A similar trend occurred between day 3 and 24POST: a moderate decrease from day 3 to day 4 (ES = -1.02 [-1.67. -0.35]) was followed by a very large increase from day 4 to 24POST (ES = 1.68 [0.46 , 2.85]). Lastly, a small decline was found from 24POST to 48POST (ES = -0.31 [-1.08 , 0.47]). Compared to day 1 of the training camp, the perceived sleep quality was higher at 24POST (ES = 0.41 [-0.65 , 1.44], mean difference: 8.4 [-16 , 32.8]) and 48POST (ES = 0.07 [-1 , 1.13], mean difference: 1.6 [-26.7 , 30]) with a trivial to small ES.

Changes after the termination of the orienteering training camp

Figure 6.3 also presented the mean changes and individual ratings of all participants (n = 11) immediately after (POST4), 24 hours (24POST) and 48 hours (48POST) after the final day of the orienteering training camp. The magnitude of these changes is summarised in Table 6.3. From POST4 to 48POST, a consistent improvement was reported in the majority of the variables. There was a progressive increase in the ratings of motivation and BRUMSV, as well as a constant decrease in MF, PF, tiredness, BRUMSF, and BRUMSC. The PF ratings showed a moderate decrease from POST4 to 24POST and continued to decrease to a moderate extent from 24POST to 48POST. However, the stress rating was the only variable to report a further moderate increase from POST4 to 24POST, before displaying a small decrease from 24POST to 48POST. Despite these improvements, the ratings of MF remained moderately higher and BRUMSV moderately lower at 48POST compared to PRE1.

Table 6.3 The extent of the changes in all outcome variables immediately, 24-hours and 48-hours after the last training session of the orienteering training camp. Data from all participants (n = 11).

Variable	POST4 vs 24POST		24POST vs 48POST		PRE1 vs 48POST	
	Mean difference [95%CI]	**Effect size [95%CI]**	**Mean difference [95%CI]**	**Effect size [95%CI]**	**Mean difference [95%CI]**	**Effect size [95%CI]**
MF	-20.4 [-40.5 , -0.2]	-1.04 [-2.02 , -0.01]*	-8.1 [-22.3 , 6.1]	-0.35 [-0.91 , 0.22]	17.3 [-1.7 , 36.3]	0.86 [-0.07 , 1.75]*
Motivation	19 [7.2 , 30.8]	0.71 [0.2 , 1.19]*	7.4 [-0.6 , 15.4]	0.35 [-0.02 , 0.7]	5.2 [-13.6 , 23.9]	0.22 [-0.48 , 0.9]
PF	-13.8 [-27.6 , 0]	-0.69 [-1.34 , 0]*	-14.4 [-36.7 , 8]	-0.68 [-1.64 , 0.31]*	9.4 [-11.8 , 30.6]	0.46 [-0.49 , 1.39]
Stress	13.3 [-0.7 , 27.2]	0.77 [-0.03 , 1.54]*	-7.4 [-21.9 , 7.2]	-0.43 [-1.2 , 0.35]	2.4 [-11.7 , 16.5]	0.12 [-0.53 , 0.78]
Tiredness	-5.9 [-19.3 , 7.5]	-0.3 [-0.91 , 0.32]	-14.4 [-26 , -2.7]	-0.67 [-1.22 , -0.1]*	0.5 [-13.5 , 14.6]	0.03 [-0.57 , 0.62]
Vigour	1.5 [-0.5 , 3.6]	0.56 [-0.15 , 1.24]	1.3 [-0.7 , 3.2]	0.45 [-0.2 , 1.07]	-3.3 [-5 , -1.5]	-1.02 [-1.65 , -0.36]*
Fatigue	-3 [-5.3 , -0.7]	-0.92 [-1.64 , -0.17]*	-1.9 [-3.4 , -0.4]	-0.58 [-1.03 , -0.1]	0.7 [-2.2 , 3.6]	0.2 [-0.52 , 0.92]
Confusion	-1.7 [-3.5 , 0]	-0.79 [-1.54 , 0]*	-0.9 [-1.7 , -0.1]	-1 [-1.89 , -0.08]*	-1.5 [-3 , 0.1]	-0.85 [-1.71 , 0.04]*

*: Moderate extent of change in the comparison (ES ≥ 0.6).

Perceived causes of mental fatigue during orienteering training

There were a total of nine perceived causes of MF identified based on 38 responses. The most frequently cited were the length of the course (24%) and the prolonged period of concentration (24%). The next common causes were the technical and physical demands of the training (both 21%), along with distractions from competitors and/or the environment (21%). The remaining causes included inadequate sleep or poor sleep quality (13%), multiple training sessions (11%), stress and/or tiredness (8%), and route selection (5%).

Supplementary analysis to address individual random effect of individuals

The likelihood ratio tests comparing fixed effects models and mixed-effects models with random intercepts for participants revealed significant improvements in model fit for the ratings of MF ($\chi^2(1) = 25.8$, $p < 0.001$), motivation ($\chi^2(1) = 30.19$, $p < 0.001$), PF ($\chi^2(1) = 31.71$, $p < 0.001$), tiredness ($\chi^2(1) = 33.97$, $p < 0.001$), stress ($\chi^2(1) = 18.07$, $p < 0.001$), BRUMSV ($\chi^2(1) = 11.61$, $p < 0.001$), BRUMSF ($\chi^2(1) = 42.03$, $p < 0.001$), and BRUMSC ($\chi^2(1) = 42.03$, $p < 0.001$) during the 4-day simulated orienteering competition camp. These results indicate that the inclusion of a random intercept for individual variability significantly improves the model fit when analysing the pre- to post-training changes across all outcome variables. According to the model comparison in Table 6.4, the random intercept models reported the lowest AIC and BIC values across all outcome variables for the pre- and post-training changes, suggesting the random intercept model provides a greater model fit than the more complex models. Additionally, the likelihood ratio tests for the models incorporating random slopes for gender and/or time did not show significant improvements in model fit ($p > 0.05$). This lack of significant improvements further supports the selection of the random intercept model. Therefore, the random intercept model was selected as the most appropriate for further analysis of all outcome variables throughout the orienteering training camp.

Table 6.4 The model comparison between random intercept model and random intercept plus random slopes model for pre- and post-orienteering training.

Variable	Model	AIC	BIC	Log-likelihood	χ²	df	p
MF	Random Intercept (Participant ID)	748.06	760.21	-369.03	-	-	-
	Random Slope: Participant x Gender	751.89	768.90	-368.94	0.17	2	0.92
	Random Slope: Participant x Time	750.01	767.03	-368.01	1.87	0	
	Random Slopes: Participant x Gender x Time	755.70	780.01	-367.85	0.31	3	0.96
Motivation	Random Intercept (Participant ID)	767.27	779.42	-378.63	-	-	-
	Random Slope: Participant x Gender	770.09	787.10	-378.04	1.18	2	0.55
	Random Slope: Participant x Time	770.18	787.20	-378.09	0	0	-
	Random Slopes: Participant x Gender x Time	774.39	798.70	-377.20	1.79	3	0.62
PF	Random Intercept (Participant ID)	754.37	766.52	-372.18	-	-	-
	Random Slope: Participant x Gender	757.45	774.46	-371.72	0.92	2	0.63
	Random Slope: Participant x Time	757.18	774.20	-371.59	0.27	0	-
	Random Slopes: Participant x Gender x Time	762.11	786.42	-371.06	1.07	3	0.79
Stress	Random Intercept (Participant ID)	726.66	738.81	-358.33	-	-	-
	Random Slope: Participant x Gender	729.58	746.59	-357.79	1.08	2	0.58
	Random Slope: Participant x Time	729.12	746.14	-357.56	0.45	0	-
	Random Slopes: Participant x Gender x Time	732.42	756.73	-356.21	2.71	3	0.44
Tiredness	Random Intercept (Participant ID)	735.10	747.25	-362.55	-	-	-
	Random Slope: Participant x Gender	739.09	756.10	-362.54	0.01	2	1
	Random Slope: Participant x Time	733.21	750.22	-359.60	5.88	0	-
	Random Slopes: Participant x Gender x Time	739.00	763.30	-359.50	0.21	3	0.98
BRUMSV	Random Intercept (Participant ID)	430.39	442.55	-210.20	-	-	-
	Random Slope: Participant x Gender	432.58	449.60	-209.29	1.81	2	0.40
	Random Slope: Participant x Time	431.44	448.45	-208.72	1.14	0	-
	Random Slopes: Participant x Gender x Time	433.04	457.35	-206.52	4.4	3	0.22
BRUMSF	Random Intercept (Participant ID)	438.67	450.82	-214.33	-	-	-
	Random Slope: Participant x Gender	442.66	459.68	-214.33	0	2	1
	Random Slope: Participant x Time	442.65	459.67	-214.33	0.01	0	-
	Random Slopes: Participant x Gender x Time	447.21	471.52	-213.61	1.44	3	0.7
BRUMSC	Random Intercept (Participant ID)	370.21	382.36	-180.10	-	-	-
	Random Slope: Participant x Gender	374.18	391.20	-180.09	0.02	2	0.99
	Random Slope: Participant x Time	370.08	387.10	-178.04	4.10	0	-
	Random Slopes: Participant x Gender x Time	376.08	400.39	-178.04	0	3	1

The random intercept estimates for each variable for each participant before and after the orienteering preparation camp are presented in Table 6.5. Individual differences were observed across all outcome variables. For instance, the random intercept estimates for perceived MF ratings ranged from -21.37 to 15.57. Similar variation was found in the ratings for motivation (-18.17 to 31.16), PF (-29.75 to 16.96), stress (-11.41 to 15.34), and tiredness (-19.28 to 22.04). These results highlight the individual variation in psychological responses, emphasising the importance of incorporating the random effects of participants into the model to ensure an accurate interpretation of the results.

Table 6.5 The random intercepts estimate of each participant based on before and after orienteering competition preparation camp Linear Mixed Model.

Variable	ID	Random intercept estimate	Variable	ID	Random intercept estimate
MF	1	15.57	Motivation	1	-18.17
	2	-8.32		2	5.69
	3	5.79		3	4.08
	4	-21.37		4	31.16
	5	8.44		5	-15.63
	6	5.58		6	-10.03
	7	-0.75		7	-5.26
	8	12.41		8	4.76
	9	-5.46		9	2.68
	10	2.31		10	-4.32
	11	-14.19		11	5.04
PF	1	15.36	Tiredness	1	22.04
	2	-8.53		2	-5.02
	3	0.79		3	13.91
	4	-29.75		4	-19.28
	5	16.96		5	16.16
	6	7.03		6	-3.17
	7	-2.59		7	-1.02
	8	6.16		8	0.46
	9	-3.14		9	-10.07
	10	7.56		10	-6.6
	11	-9.86		11	-7.41
Stress	1	4.56	BRUMSV	1	-1.03
	2	-4.95		2	-0.63
	3	4.55		3	-1.96
	4	-11.41		4	3.37
	5	15.34		5	-1.46
	6	-4.52		6	-0.28
	7	-1.07		7	-0.67
	8	-0.97		8	0.45
	9	7.37		9	-0.63
	10	-2.89		10	1
	11	-6.02		11	1.84
BRUMSF	1	3.42	BRUMSC	1	0.2
	2	-1.5		2	-1.33
	3	1.98		3	1.43

4	-4.31	4	-1.33
5	3.13	5	1.74
6	0.61	6	-0.31
7	-2.94	7	-0.31
8	2.73	8	1.33
9	-3.9	9	1.02
10	1.53	10	-1.23
11	-0.75	11	-1.22

Significant effects of time across pre- and post-orienteering competition preparation camp were observed for perceived MF ($F(7, 59.1) = 10.52$, $p < 0.001$), PF ($F(7, 59.2) = 8.83$, $p < 0.001$), tiredness ($F(7, 59.4) = 2.8$, $p = 0.014$), BRUMSV ($F(7, 59.3) = 5.09$, $p < 0.001$), and BRUMSF ($F(7, 59.3) = 6.5$, $p < 0.001$). However, no significant time effects were reported for the ratings of motivation ($F(7, 59.5) = 1.41$, $p = 0.217$), stress ($F(7, 59.7) = 0.171$, $p = 0.99$), or BRUMSC ($F(7, 59) = 1.51$, $p = 0.181$). The Bonferroni post-hoc tests in Table 6.6 revealed consistent time-related changes for perceived MF, PF, tiredness, BRUMSV and BRUMSF. Perceived MF showed a progressive increase with significant differences observed at each post-training time point, as well as the highest differences at POST4 compared to PRE1. A similar pattern was observed in PF ratings, with the largest increase also reported at POST4 when compared to PRE1. Tiredness and BRUMSF ratings increased significantly at POST2, POST3, and POST4. In contrast, BRUMSV showed a consistent and significant decline after each training session across the four-day training camp. Additionally, no significant main effects of gender were found for any outcome variables ($p > 0.05$), indicating that changes in measured outcome variables were similar between male and female participants. Furthermore, no significant interaction effects between time and gender were reported for the ratings of perceived MF ($F(7, 59.1) = 1.42$, $p = 0.214$), motivation ($F(7, 59.5) = 0.361$, $p = 0.921$), PF ($F(7, 59.2) = 0.37$, $p = 0.915$), stress ($F(7, 59.7) = 1.09$, $p = 0.382$), BRUMSV ($F(7, 59.3) = 0.7$, $p = 0.672$), BRUMSF ($F(7, 59.2) = 0.59$, $p = 0.758$), and BRUMSC ($F(7, 59) = 0.09$, $p = 0.999$). Although a significant interaction effect between time and gender was observed in the ratings of tiredness ($F(7, 59.4) = 2.31$, $p = 0.037$), the Bonferroni post-hoc analyses did not reveal any significant differences in any comparison ($p > 0.05$).

Table 6.6 The Bonferroni post-hoc comparison of the variables during 4-day orienteering competition preparation camp.

Comparison	Variable	Estimate (β) ± SE	df	t	p	95%CI	Cohen's d	Descriptor
POST1 vs PRE1	MF	28.4 ± 6.3	59	4.51	< 0.001**	15.8, 41	1.93	Large
	PF	32.38 ± 6.54	59	4.95	< 0.001**	19.3, 45.5	2.12	Very large
	BRUMSF	3.5 ± 1.02	59	3.43	0.031*	1.5, 5.5	1.47	Large
POST2 vs PRE1	MF	36.81 ± 6.56	59.4	5.61	< 0.001**	23.7, 49.9	2.5	Very large
	PF	36.03 ± 6.81	59.3	5.3	< 0.001**	22.4, 49.7	2.35	Very large
	Tiredness	23.78 ± 6.73	59.4	3.53	0.023*	10.3, 37.2	1.57	Large
	BRUMSV	-4.93 ± 1.18	59.6	-4.17	0.003*	-7.3, -2.6	1.86	Large
	BRUMSF	4.75 ± 1.06	59.2	4.47	< 0.001**	2.6, 6.8	2	Very large
POST3 vs PRE1	MF	39.27 ± 6.56	59.4	6	< 0.001**	26.2, 52.4	2.67	Very large
	PF	31.82 ± 6.81	59.3	4.67	< 0.001**	18.2, 45.5	2.08	Very large
PRE4 vs PRE1	MF	21.23 ± 6.3	59	3.37	0.037*	8.6, 33.8	1.44	Large
	PF	23.17 ± 6.54	59	3.54	0.022*	10.1, 36.3	1.51	Large
POST4 vs PRE1	MF	46.08 ± 6.3	59	7.31	< 0.001**	33.5, 58.7	3.13	Very large
	PF	37.63 ± 6.54	59	5.75	< 0.001**	24.5, 50.7	2.46	Very large
	Tiredness	21.88 ± 6.47	59	3.38	0.036*	8.9, 34.8	1.45	Large
	BRUMSV	-6.2 ± 1.14	59	-5.46	< 0.001**	-8.5, -3.9	2.34	Very large
	BRUMSF	5.73 ± 1.02	59	5.63	< 0.001**	3.7, 7.8	2.41	Very large
POST4 vs PRE2	MF	28.27 ± 6.56	59.4	4.31	0.002*	15.2, 41.4	1.92	Large
	PF	27.57 ± 6.81	59.3	4.05	0.004*	13.9, 41.2	1.8	Large
	BRUMSF	4.57 ± 1.06	59.2	4.31	0.002*	2.5, 6.7	1.92	Large
POST2 vs PRE2	PF	25.96 ± 6.97	59	3.72	0.012*	12, 39.9	1.7	Large
	BRUMSF	3.58 ± 1.09	59	3.3	0.046*	1.4, 5.8	1.5	Large
POST4 vs PRE3	MF	26.73 ± 6.56	59.4	4.08	0.004*	13.6, 39.9	1.82	Large
	PF	26.61 ± 6.81	59.3	3.91	0.007*	13, 40.2	1.74	Large
	BRUMSF	3.9 ± 1.06	59.2	3.68	0.014*	1.8, 6	1.64	Large
POST4 vs PRE4	MF	24.85 ± 6.3	59	3.94	0.006	11.7, 38	1.69	Large
PRE2 vs POST1	PF	-22.32 ± 6.81	59.3	-3.28	0.049*	-36, -8.7	1.46	Large
PRE3 vs POST2	PF	-25 ± 6.97	59	-3.59	0.019*	-39, -11.1	1.63	Large
POST4 vs POST1	BRUMSV	-3.95 ± 1.14	59	-3.48	0.027*	-6.2, -1.7	1.49	Large

SE: Standard errors; df: degree of freedom; *: $p < 0.05$ **; $p < 0.001$.

Changes after the termination of the orienteering training camp

The likelihood ratio tests comparing the fixed effects models and the random intercept model for all outcome variables demonstrated that the inclusion of a random intercept for participants significantly improved model fits except for the ratings of BRUMSC. Specifically, significant improvements in model fit were observed in the ratings of MF ($\chi^2(1) = 15.15$, $p < 0.001$), motivation ($\chi^2(1) = 33.54$, $p < 0.001$), PF ($\chi^2(1) = 14.93$, $p < 0.001$), stress ($\chi^2(1) = 15.54$, $p < 0.001$), tiredness ($\chi^2(1) = 24.74$, $p < 0.001$), BRUMSV ($\chi^2(1) = 10.39$, $p = 0.001$), and BRUMSF ($\chi^2(1) = 12.4$, $p < 0.001$). However, no significant improvement were reported with the inclusion of a random intercept for BRUMSC ratings ($\chi^2(1) = 1.35$, $p = 0.244$), indicating there was insufficient individual variability to include random intercepts. Therefore, the fixed effects model is used for BRUMSC for further analysis to avoid unnecessary model complexity.

According to Table 6.7, the random intercept with both random gender and time slopes model was excluded due to convergence issues. The model comparison in Table 6.7 for POST4, 24POST, and 48POST orienteering training focused on the random intercept model, the random intercept model with a random slope for gender, and the random intercept model with a random slope for time. As summarised in Table 6.7, the random intercept model consistently provided the best fit for most outcome variables, including MF, motivation, PF, stress, BRUMSV, and BRUMSF, as the addition of random slopes for gender and/or time did not significantly improve model fit. However, for tiredness ratings, the random intercept model with a random slope for gender demonstrated a significantly better fit than the other models. Accordingly, the random intercept model was utilised for all outcome variables except for tiredness, where the random intercept model with a random gender slope was used.

Table 6.7 The model comparison between random intercept model and random intercept plus random slopes model for the changes after the orienteering competition preparation camp.

Variable	Model	AIC	BIC	Log-likelihood	χ^2	df	p
MF	Random Intercept (Participant ID)	301.41	308.89	-145.70	-	-	-
	Random Slope: Participant x Gender	303.92	314.40	-144.96	1.49	2	0.48
	Random Slope: Participant x Time	301.69	312.17	-143.85	2.23	0	-
Motivation	Random Intercept (Participant ID)	293.49	300.97	-141.74	-	-	-
	Random Slope: Participant x Gender	297.13	307.60	-141.56	0.36	2	0.83
	Random Slope: Participant x Time	292.35	302.83	-139.18	4.77	0	-
PF	Random Intercept (Participant ID)	295.39	302.88	-142.70	-	-	-
	Random Slope: Participant x Gender	293.82	304.30	-139.91	5.57	2	0.06
	Random Slope: Participant x Time	298.61	309.08	-142.30	0	0	-
Stress	Random Intercept (Participant ID)	286.93	294.41	-138.46	-	-	-
	Random Slope: Participant x Gender	287.89	298.37	-136.95	3.04	2	0.22
	Random Slope: Participant x Time	290.91	301.38	-138.46	0	0	-
Tiredness	Random Intercept (Participant ID)	293.76	301.25	-141.88	-	-	-
	Random Slope: Participant x Gender	290.10	300.57	-138.05	7.66	2	0.022*
	Random Slope: Participant x Time	296.19	306.66	-141.09	0	0	-
BRUMSV	Random Intercept (Participant ID)	163.09	170.57	-76.546	-	-	-
	Random Slope: Participant x Gender	163.56	174.03	-74.779	3.53	2	0.17
	Random Slope: Participant x Time	167.09	177.57	-76.546	0	0	-
BRUMSF	Random Intercept (Participant ID)	170.46	177.94	-80.228	-	-	-
	Random Slope: Participant x Gender	173.36	183.83	-79.679	1.1	2	0.58
	Random Slope: Participant x Time	173.04	183.51	-79.520	0.32	0	-

The random intercept estimates for each variable excluding BRUMSC for each participant immediately after, 24 hours, and 48 hours post-orienteering preparation camp are presented in Table 6.8. A narrow range of individual variation was found in the ratings of MF (-4.33 to 4.35) and PF (-4.85 to 6.29). In contrast, wide individual differences were observed in the ratings of motivation (-21.59 to 33.11), stress (-12.38 to 6.48), and tiredness (-27.07 to 19). These findings highlight the importance of accounting for the random effects of participants in further analyses.

Table 6.8 The random intercepts estimate of each participant based on immediately after, 24-hour and 48-hour post orienteering competition preparation camp Linear Mixed Model.

Variable	ID	Random intercept estimate	Variable	ID	Random intercept estimate
MF	1	-0.46	Motivation	1	7.32
	2	-2.13		2	-21.6
	3	-4.33		3	-5.15
	4	-3.03		4	33.11
	5	4.35		5	-8.76
	6	3.63		6	-20.21
	7	-2.09		7	-22.01
	8	-0.1		8	25.09
	9	1.42		9	26
	10	1.66		10	-19.67
	11	1.07		11	5.88
PF	1	6.29	Stress	1	4.42
	2	-2.51		2	-2.37
	3	-4.85		3	10.38
	4	-4.62		4	-12.38
	5	5.2		5	6.48
	6	2.94		6	-5.58
	7	-4.96		7	0.19
	8	-2.4		8	-2.03
	9	3.35		9	1.87
	10	1.69		10	-0.49
	11	-0.13		11	-0.49
Tiredness	1	14.39	BRUMSV	1	-2.66
	2	9.87		2	-2.11
	3	-27.07		3	2.67
	4	-29.61		4	3.77
	5	19		5	-2.25
	6	13.91		6	-0.06
	7	-13.22		7	0.49
	8	2.52		8	1.17
	9	11.85		9	-2.11
	10	-4.01		10	0.71
	11	2.36		11	0.39
BRUMSF	1	0.39			
	2	-0.13			
	3	-2.29			
	4	-3.07			

5	3.72
6	1.11
7	-1.24
8	0.66
9	-2.48
10	2.44
11	0.89

The results identified significant time effects for perceived MF ($F(2, 18.1) = 6.2$, $p = 0.009$), motivation ($F(2, 16.8) = 11.58$, $p < 0.001$), PF ($F(2, 17.3) = 17.2$, $p < 0.001$), tiredness ($F(2, 18.5) = 10.8$, $p < 0.001$), BRUMSV ($F(2, 15.1) = 6.61$, $p = 0.009$), and BRUMSF ($F(2, 17.8) = 13.5$, $p < 0.001$), but not for stress ratings ($F(2, 18) = 2.16$, $p = 0.144$). The Bonferroni post-hoc test in Table 6.9 revealed a significant decrease in the ratings of perceived MF, PF, tiredness, and BRUMSF, along with a significant increase in the ratings of motivation and BRUMSV from POST4 to 48POST. In contrast, the insignificant changes in stress ratings suggest that the stress levels of participants remained stable 24 and 48 hours after the four-day training camp. Similar to pre- to post-training session findings, no significant main effects of gender were found for any outcome variables ($p > 0.05$), highlighting similar patterns of changes between male and female participants. Moreover, no significant interaction effects between time and gender were found in perceived MF ($F(2, 20.4) = 0.99$, $p = 0.388$), motivation ($F(2, 17.3) = 0.06$, $p = 0.938$), PF ($F(2, 16.4) = 2.62$, $p = 0.103$), stress ($F(2, 19.5) = 0.32$, $p = 0.731$), tiredness ($F(2, 17.6) = 2.77$, $p = 0.09$), BRUMSV ($F(2, 15.9) = 1.95$, $p = 0.175$), and BRUMSF ($F(2, 18.7) = 0.89$, $p = 0.429$). Additionally, the overall fixed effects model for BRUMSC ratings was significant ($F(3, 29) = 3.77$, $p = 0.021$). However, no significant main effects of time ($\beta = -1.55$, $SE = 1.28$, $t(29) = -1.21$, $p = 0.237$), gender ($\beta = -0.12$, $SE = 1.71$, $t(29) = -0.07$, $p = 0.943$), nor a significant interaction effects between time and gender ($\beta = 0.15$, $SE = 0.79$, $t(29) = 0.19$, $p = 0.851$).

Table 6.9 The Bonferroni post-hoc comparison of the variables immediately post, 24-hour and 48-hour post 4-day training camp.

Comparison	Variable	Estimate (β) ± SE	df	t	p	95%CI	Cohen's d	Descriptor
24POST vs POST4	Motivation	19 ± 5.62	17.1	3.38	0.011*	7.2, 30.9	1.45	Large
	PF	-15 ± 5.59	16.2	-2.68	0.049*	-26.8, -3.2	-1.15	Moderate
	BRUMSF	-3.1 ± 0.97	17.3	-3.19	0.016*	-5.1, -1.1	-1.37	Large
48POST vs POST4	MF	-29.5 ± 8.64	17.7	-3.41	0.009*	-47.7, -11.3	-1.46	Large
	Motivation	26.19 ± 5.63	17.1	4.66	< 0.001**	14.3, 38.1	2	Very large
	PF	-34.6 ± 6.06	17.3	-5.72	< 0.001**	-47.4, -21.8	-2.46	Very large
	tiredness	-23.84 ± 5.43	17.5	-4.39	0.001*	-35.3, 12.4	-2.05	Very large
	BRUMSV	2.96 ± 0.82	17.2	3.63	0.006*	1.2, 4.7	1.56	Very large
	BRUMSF	-5.02 ± 0.97	17.3	-5.16	< 0.001**	-7.1, -3	-2.21	Very large
48POST vs 24POST	PF	-19.7 ± 6.06	17.3	-3.25	0.014*	-32.5, -6.9	-1.5	Large
48POST vs 24POST	Tiredness	-16.9 ± 5.43	17.5	-3.11	0.019*	-28.3, -5.5	-1.45	Large
24POST vs PRE1	MF	24.87 ± 7.43	18	3.35	0.011*	9.3, 40.5	1.43	Large
	BRUMSV	-4.53 ± 1	18	-4.51	< 0.001**	-6.6, -2.4	-1.93	Large
48POST vs PRE1	BRUMSV	-3.33 ± 1	18	-3.32	0.011*	-5.4, -1.2	-1.42	Large

SE: Standard errors; df: degree of freedom; *: p < 0.05 **; p < 0.001.

When comparing the mode of all outcome variables at 24 and 48 hours after the training camp to PRE1, the random intercept model demonstrated a significantly better model fit than the fixed effects model for most outcome variables. The significant improvements in model fit were found in the ratings of MF ($\chi^2(1) = 16.82$, $p < 0.001$), motivation ($\chi^2(1) = 20.3$, $p < 0.001$), PF ($\chi^2(1) = 15.47$, $p < 0.001$), stress ($\chi^2(1) = 18.53$, $p < 0.001$), tiredness ($\chi^2(1) = 19.96$, $p < 0.001$), BRUMSV ($\chi^2(1) = 6.5$, $p < 0.05$), and BRUMSF ($\chi^2(1) = 7.61$, $p < 0.01$). However, the inclusion of a random intercept for participants did not significantly improve the model fit for BRUMSC ratings ($\chi^2(1) = 0.19$, $p = 0.66$), indicating that a fixed effects model is more appropriate for this variable.

Due to convergence issues with the random intercept models that included both gender and time as random slopes, the model comparison for PRE1, 24POST, and 48POST in Table 6.10 focused on the random intercept model, the random intercept with a random slope for gender, and the random intercept with a random slope for time. The summary in Table 6.10 consistently shows that the random intercept model provides the best fit across all outcome variables, making it the most appropriate model for further analysis.

Table 6.10 The model comparison between random intercept model and random intercept plus random slopes model for the comparison between before the first orienteering training and changes after the orienteering competition preparation camp.

Variable	Model	AIC	BIC	Log-likelihood	χ^2	df	p
MF	Random Intercept (Participant ID)	303.06	310.54	-146.53	-	-	-
	Random Slope: Participant x Gender	304.12	314.60	-145.06	2.94	2	0.230
	Random Slope: Participant x Time	305.93	316.40	-145.96	0	0	-
Motivation	Random Intercept (Participant ID)	301.84	309.32	-145.92	-	-	-
	Random Slope: Participant x Gender	304.69	315.16	-145.34	1.15	2	0.561
	Random Slope: Participant x Time	304.97	315.44	-145.48	0	0	-
PF	Random Intercept (Participant ID)	307.16	314.64	-148.58	-	-	-
	Random Slope: Participant x Gender	311.16	321.64	-148.58	0	2	1
	Random Slope: Participant x Time	311.16	321.64	-148.58	0	0	-
Stress	Random Intercept (Participant ID)	289.52	297.00	-139.76	-	-	-
	Random Slope: Participant x Gender	289.29	299.76	-137.64	4.23	2	0.121
	Random Slope: Participant x Time	292.18	302.66	-139.09	0	0	-
Tiredness	Random Intercept (Participant ID)	297.17	304.65	-143.58	-	-	-
	Random Slope: Participant x Gender	298.31	308.79	-142.16	2.85	2	0.240
	Random Slope: Participant x Time	297.53	308.00	-141.76	0.79	0	-
BRUMSV	Random Intercept (Participant ID)	178.01	185.49	-84.003	-	-	-
	Random Slope: Participant x Gender	180.49	190.97	-83.245	1.52	2	0.469
	Random Slope: Participant x Time	182.00	192.48	-84.000	0	0	-
BRUMSF	Random Intercept (Participant ID)	179.96	187.44	-84.980	-	-	-
	Random Slope: Participant x Gender	183.52	194.00	-84.761	0.44	2	0.803
	Random Slope: Participant x Time	183.76	194.23	-84.879	0	0	-

The random intercept estimates for each variable across all participants measured before the first day of the orienteering preparation camp, as well as 24 hours and 48 hours post-camp, are presented in Table 6.11. Individual variability was observed in all outcome variables, with the exception of the PF ratings, where minimal individual differences or convergence issues may have resulted in estimates appearing as zero. These results highlight the importance of accounting for individual variability in further analysis as participants experienced different levels of each subjective measure.

Table 6.11 The random intercepts estimate of each participant based on immediately after, 24-hour and 48-hour post orienteering competition preparation camp Linear Mixed Model.

Variable	ID	Random intercept estimate	Variable	ID	Random intercept estimate
MF	1	-3.53	Motivation	1	-6.35
	2	-4.19		2	-11.9
	3	-15.65		3	9.73
	4	-4.66		4	25.01
	5	12.48		5	-9.96
	6	4.83		6	-13.66
	7	-3.16		7	-8.11
	8	0.63		8	1.76
	9	4.46		9	11.95
	10	6.16		10	-3.01
	11	2.63		11	4.54
Stress	1	0.67	Tiredness	1	-4.46
	2	-1.79		2	1.81
	3	8.7		3	-12.13
	4	-19.08		4	-15.85
	5	17.88		5	15.77
	6	1.08		6	19.72
	7	-4.29		7	-2.36
	8	-5.82		8	-6.79
	9	0.45		9	-1.44
	10	-4.29		10	-5.15
	11	6.5		11	10.88
BRUMSV	1	-0.193	BRUMSF	1	-0.5
	2	-1.55		2	0.55
	3	0.84		3	-1.54
	4	2.19		4	-1.96
	5	-2.06		5	2.24
	6	-1.48		6	1.19
	7	-0.9		7	-1.54
	8	1.16		8	1.6
	9	0		9	-2.19
	10	1.42		10	1.61
	11	0.58		11	0.55

Significant effects of time were observed in the ratings of perceived MF ($F(2, 18) = 5.81$, $p = 0.011$), tiredness ($F(2, 18) = 4.12$, $p = 0.034$), and BRUMSV ($F(2, 18) = 10.94$, $p < 0.001$).

These results indicate that perceived MF and tiredness remained higher than the PRE1 value, while BRUMSV remained lower compared to PRE1 values. However, the Bonferroni post-hoc analyses in Table 6.9 revealed significant impairments in perceived MF and BRUMSV but not in tiredness ratings. In contrast, no significant effects of time were reported in the ratings of motivation ($F(2, 18) = 0.49$, $p = 0.0621$), PF ($F(2, 27) = 3.17$, $p = 0.058$), stress ($F(2, 18) = 1.27$, $p = 0.304$), and BRUMSF ($F(2, 18) = 2.79$, $p = 0.088$), indicating that these variables had recovered to similar levels to PRE1 at 48POST. Additionally, no significant gender effects were reported in all outcome variables, suggesting that changes in the comparison were similar across male and female participants. Furthermore, no significant interaction effects between time and gender were found in the ratings of perceived MF ($F(2, 18) = 0.44$, $p = 0.651$), motivation ($F(2, 18) = 0.15$, $p = 0.86$), PF ($F(2, 27) = 1.13$, $p = 0.338$), stress ($F(2, 18) = 0.59$, $p = 0.567$), tiredness ($F(2, 18) = 1.84$, $p = 0.187$), BRUMSV ($F(2, 18) = 0.36$, $p = 0.7$), and BRUMSF ($F(2, 18) = 0$, $p = 0.996$). For BRUMSC, the overall fixed effects model was not significant, $F(3, 29) = 1.59$, $p = 0.212$. There were no significant effects of time ($\beta = -0.93$, $SE = 1.10$, $t(29) = -0.85$, $p = 0.404$), gender ($\beta = -0.08$, $SE = 1.47$, $t(29) = -0.05$, $p = 0.958$), or interaction between time and gender ($\beta = 0.13$, $SE = 0.68$, $t(29) = 0.20$, $p = 0.846$).

6.4 Discussion

This study investigated the effects of orienteering training camp on well-trained orienteers' subjective ratings of MF and other psychological responses. A moderate increase in perceived MF was reported after each training session, with elevated ratings persisting on the following training day and failing to recover to PRE1 values. The highest perceived MF ratings were recorded on the fourth day of the camp, indicating a progressive accumulation effect. Importantly, even 48 hours after the termination of the training camp, perceived MF did not fully recover to PRE1 values.

Acute changes in perceived mental fatigue after orienteering training

The combined analysis of pre-and post-orienteering training sessions revealed a moderate increase in perceived MF, supporting the orienteering expert’s consensus in Chapter 4 that orienteers experience MF during training sessions (Lam et al., 2023). These findings also support previous findings with elite netballers, where participation in sport alone can acutely induce MF (Russell et al., 2019). However, the extent to which this moderate increase in perceived MF affects subsequent orienteering performance is unclear. For example, Batista (2021) reported a trivial increase (ES = 0.20) in the completion time of a 3.1km orienteering race following a 30-minute MF protocol. However, this approach has been criticised for its low ecological validity as discussed in section 2.4.1. In contrast, Coutinho et al. (2017) employed a more ecologically valid MF protocol involving 20 minutes of physical activity and found a moderate increase in perceived MF (ES = 0.6), along with a reduced ability to efficiently process environmental information, consequently affecting the tactical performance of soccer players.

All participants in this research followed the same training program and competed in various simulated races every day during the orienteering competition preparation camp. It is important to note that the impact of MF on orienteering performance was not explicitly compared or analysed in this study. However, the ES obtained in this study suggests that future research should consider using orienteering training as a sport-specific method to elicit MF when investigating its impact on orienteering decision-making performance. This recommendation is supported by previous research where a combined physical and cognitive load MF protocol impaired both perceived MF ratings and football performance (Coutinho et al., 2017). Although the confidence interval of ES in the combined analysis was wide (0.66 to 1.45), the lower limit of the ES still exceeds 0.6, suggesting a moderate impact on orienteering performance. Given that the ability to process and respond to environmental information is fundamental to successful navigation in orienteering, a moderate increase in perceived MF can negatively affect orienteering performance.

This study also highlighted the consecutive changes in perceived MF throughout the 4-day orienteering training camp, revealing a delayed recovery where perceived MF did not return to a similar level as the pre-training values between days 1 to 4. Due to participants competing in multiple simulated races per day, it was not feasible to identify any particular effects of the race distance on perceived MF during the training camp. This limited the ability to evaluate the impact of race distance on perceived MF, although this aspect was addressed under real competition in Chapter 5. It remains debatable whether a similar accumulation of MF occurs during multiple days of orienteering competition, especially since previous review reports that MF is related to the amount of effort invested (Giboin & Wolff, 2019), and Chapter 4 reported that the nature of MF differs between training and competition (Lam et al., 2023). The simulated competition preparation camp in this study differed from actual competitions in terms of atmosphere, duration, and psychological load. Although all participants shared accommodation and followed similar daily routines, inter-individual differences may have affected recovery. For instance, this study did not assess objective sleep quality, despite evidence suggesting its relevance to MF (Loch et al., 2020). A confounding factor was the participants' arrival at the training site a day prior to the camp. Previous research has indicated that the "first-night effect" can impair sleep quality in elite athletes (Hof zum Berge, Kellmann, & Jakowski, 2021), which may compromise mental recovery due to changes in sleeping environments and routines (Loch et al., 2020). Given the physically and cognitively demanding schedule during training camp, it is difficult to determine whether the observed changes were caused by training or by inadequate recovery. It is therefore advised that future investigations monitor sleep quality to better explain the overall recovery of the athletes. As our findings relied on subjective MF ratings, the findings reflect psychological responses specific to the context of this training camp and may not be generalisable to other training environments or actual competitions. The amount of time needed to fully recover from sport-induced MF remains uncertain, as previous observational studies with soccer players (Abbott et al., 2020; Thompson et al., 2020) and netball players (Russell et al., 2019) have shown that MF can negatively affect recovery.

As discussed in Section 5.4, although the 95% CIs for PRE values from days 2 to 4 overlap with those of PRE1, the mean values demonstrate a consistent upward trend over time. This pattern reflects a progressive increase in perceived MF throughout the training period, despite the variability indicated by overlapping CIs. Notably, Figure 6.3 shows that the 95%CIs for POST2–4 do not overlap with PRE1, suggesting that these changes are unlikely to be due to random variation and supporting the conclusion that orienteering training induces MF. The large ES observed on day 1, along with the moderate increases in mean values from days 2 to 4, further supports this interpretation. While the overlapping 95%CI reflects inter-individual variability, the progressive increase in the means of PRE-training value reflects the practical significance of these findings. Hopkins and Rowlands (2024) emphasise that ES should be interpreted within the context of the study, as they can provide meaningful insights into changes even when there is variability in the data. Further discussion of the limitations of the scoring methodology and statistical analysis is provided in sections 7.3.1.5-7.3.1.7.

Acute changes in other psychological variables and mood state after orienteering training

The pattern of changes in perceived PF and MF before and after orienteering training were different, especially evident in post-training values on days two and three of the camp. The progressive increase in perceived MF ratings following each training session supports the notion of an accumulating MF effect. This aligns with previous investigations using elite netball players (Russell et al., 2019; Russell et al., 2022), which also emphasised the need to manage perceived MF and PF separately. The objective of the training camp was to intentionally increase stress and training load to boost athletes' physiological development, psychological resilience and adaptability to competition demands. Although orienteering training led to acute increases in perceived MF and PF, how these short-term changes contribute to long-term adaptation remains unclear and requires future longitudinal investigation. Furthermore, the trivial to small decrease in stress ratings after orienteering training indicates that MF may not be linked to perceived stress. This finding is in line with the findings from a 2-year longitudinal study involving elite netball players, where stress and perceived MF were found to be different fatigue constructs (Russell et al., 2022). As mentioned in Chapter 4, the elevated stress ratings reported before training may be attributed to pre-competition anxiety because participants were preparing for a simulated orienteering race in this study (Lam et al., 2023).

It is also necessary to note the wide confidence interval reported when comparing the magnitude of changes between different training days, which reflects high variability in the data. Given the subjective nature of stress ratings, individual interpretations are likely to vary, contributing to this inconsistency. Similar variability was observed in other outcome variables, where the confidence intervals overlapped with zero, suggesting no statistically significant difference and indicating the presence of high individual variability. Additionally, the trivial increases in stress ratings may be explained by the fact that orienteers are used to playing in environments that require high levels of physical and mental stress (Batista et al., 2020; Eccles & Arsal, 2015). In support of this, Martin et al. (2019) found that individuals who frequently engage in a highly self-regulated environment tend to perceive less stress. Similar to previous research, the variability in participant interpretations and definitions of stress may have affected the results because the current study did not explicitly define stress for participants. To enhance measurement precision, future research should specify the type of stress being measured, such as cognitive stress or physical stress, rather than using general terminology.

Although there was a trivial to moderate increase in tiredness ratings following orienteering training, the differences in the magnitude of changes between tiredness and perceived MF indicate that MF should not be equated with increased tiredness. This supports previous observations with elite netball players, which also concluded that perceived MF is different from tiredness (Russell et al., 2022). In line with the findings in Chapter 4, the differences in changes between MF and tiredness ratings challenge the validity of the widely accepted definition of MF in the literature (Habay et al., 2021; Van Cutsem et al., 2017). To improve the conceptual clarity and measurement accuracy, future research including orienteers may benefit from adopting the orienteering-specific definition of MF developed in Chapter 4.

As reported in section 2.5.2.2, the ratings of BRUMSV and BRUMSF are negatively affected under the state of MF. The present study repeatedly observed that higher ratings of perceived MF following each training session were accompanied by decreased BRUMSV and increased BRUMSF ratings. However, due to the observational study design of this study, it is not possible to determine whether these changes were primarily caused by the presence of MF or affected by other training-related factors. Similar limitations were observed in Selmi et al. (2022), who noted a decrease in BRUMSV and an increase in BRUMSF over a two-week football training camp. These findings suggest that mentally fatigued participants tend to report lower BRUMSV and higher BRUMSF as reported in section 2.5.2.2. Additionally, BRUMSC ratings showed a small to moderate increase following orienteering training, supporting the expert consensus in Chapter 4 that confusion may occur under MF conditions. Therefore, it may be appropriate for future research to include the BRUMSC subscale when assessing the mood state of orienteers and to investigate the effectiveness of the MF interventions.

Changes in subjective outcome variables 24- and 48-hour post-camp

The ratings of perceived MF, PF, stress, tiredness, BRUMSV and BRUMSC remained impaired at 48POST compared to PRE1, in line with findings from soccer players (Abbott et al., 2018; Abbott et al., 2020; Thompson et al., 2020). Inadequate recovery has been linked to poor sleep quality during training and competition periods (Fullagar et al., 2016). Although perceived sleep quality was measured in this study, we did not record the detailed metrics such as time spent in bed, sleep-wake patterns or objective sleep quality measurements. Consequently, it remains uncertain whether the impaired psychological responses reported during and after the training camp were primarily attributed to disrupted sleep, insufficient recovery, or a combination of both. Although only trivial to small differences in perceived sleep quality were observed when comparing PRE1 to 24POST and 48POST, the sleep quality was perceived to be higher after the termination of the training camp. This may suggest that sleep disturbance may have occurred before and during training camp. However, the aim of this study was to observe the fluctuations in MF during orienteering training, future research is needed to determine whether changes in MF are influenced by perceived recovery and objective sleep metrics.

It is recognised that the training camp examined in this study was not a traditional orienteering camp, but rather a simulated competition training camp where participants completed a series of simulated races over four consecutive days. Consequently, it is not possible to determine whether orienteers would experience a similar delay in recovery during a regular pre-season training week or camp. The subjective ratings of MF and other psychological responses at 24POST and 48POST demonstrated overlapping 95%CI with previous time points. The wide 95%CI observed may reflect individual variability influenced by external factors unrelated to orienteering, which were not monitored or controlled in this study. As discussed in Chapter 4 and Thompson et al. (2020), non-sport-related activities such as academic, occupational, or personal commitments, can negatively affect MF and psychological states, contributing to the observed variability. These findings underscore the subjective and multifaceted nature of psychological responses, including MF, where individual perceptions and external factors contribute to variability. Rather than undermining the results, the variability highlighted by the wide confidence intervals emphasises the complexity of MF and its interaction with the multifactorial nature of MF, which extends beyond the scope of the monitored orienteering activities.

It is important to emphasise that this study cannot conclude whether the delayed recovery in 24POST and 48POST was primarily caused by the orienteering training camp. All participants were full-time students, and previous research has shown that education demands and non-orienteering challenges may contribute to the negative changes in MF and psychological responses (Lam et al., 2023; Thompson et al., 2020). However, as participants were on spring break during the training camp, the influence of academic responsibilities on delayed recovery is likely to be minimal. To assess the effect of simulated orienteering races on the development of MF accurately, future research should consider using a longitudinal research design to monitor daily changes across different training formats and determine whether a standard training week produces similar outcomes to those observed during a simulated orienteering training camp.

Perceived causes of mental fatigue during orienteering training

The most often reported perceived causes of MF in the current study were the "length of the course" and the "prolonged period of concentration". This suggests that tasks requiring sustained cognitive effort were perceived as primary contributors to MF during orienteering training. These findings are in line with the widely used definitions of MF in the literature (Brown et al., 2020; Habay et al., 2021; Van Cutsem et al., 2017) and the orienteering-specific definition developed in Chapter 4, which highlights the role of cognitive effort in the development of MF. The national junior orienteers also showed agreement with the findings in Chapter 4 (Lam et al., 2023), recognising the physical and technical demands of the orienteering training as potential contributing factors to MF. Interestingly, participants identified distraction as one of the perceived causes of MF, which contrasts with the orienteering expert's consensus in Chapter 4 (Lam et al., 2023). While the international orienteering experts associated distraction with the presence of other competitors and its role in increasing external stress (Lam et al., 2023), the participants in this study may have experienced distraction differently, potentially influenced by lower motivation toward the training. Previous research has found that individuals with lower motivational ratings are more susceptible to visual distraction than those who are highly motivated individuals (Herlambang, Cnossen, & Taatgen, 2021; Herlambang, Taatgen, & Cnossen, 2019), which may explain this discrepancy. Although some participants mentioned 'stress and/or tiredness' as a cause of MF in orienteering training, the subjective ratings of stress and tiredness recorded during the 4-day orienteering training did not report noticeable impairments. It is possible that the participants were referring to different forms of stressors or fatigue not captured by the self-report measures. However, due to the lack of specificity in their responses, further analysis could not be conducted to clarify these interpretations.

Individual variability in the responses

The present study examined the changes in MF and other psychological responses during a 4-day simulated orienteering competition preparation camp. Significant improvements in model fit were reported with the inclusion of random intercepts for participants for most outcome variables, including MF, PF, motivation, tiredness, stress, and the BRUMS vigour and fatigue subscales. These findings highlight the substantial individual variability among participants and reinforce the importance of accounting for this variability in statistical modelling. In line with the findings in Chapter 5 and previous observational research with elite netballers (Russell et al., 2022), the results support that orienteering training induces varied psychological responses between individuals, indicating the importance of models that incorporate individual variability to ensure accurate interpretations. A wide range of random intercept estimates was identified across participants, particularly in the ratings of motivation, stress, and tiredness. This highlights the limitations of relying solely on overall mean values, which may obscure important individual differences and lead to misleading interpretations of training-induced changes. The random intercept models were consistently favoured over more complex models with random slopes for gender or time except for BRUMSC, indicating that individual variability was effectively captured without the need to model time or gender as random effects.

Although individual variability was identified, the inclusion of random slopes for gender and/or time did not significantly improve model fit, and no interactions between time and gender were observed across most outcome variables. These findings suggest similar psychological response patterns between male and female participants, aligning with recent literature suggesting that MF may not differ significantly by gender (Habay et al., 2023). Although this study utilised a balanced gender sample (5 males and 6 females), future studies with larger sample sizes could provide deeper insights into potential gender-specific effects.

The post-hoc analyses revealed that perceived MF and PF increased progressively during the 4-day training camp, with the highest ratings recorded at POST4. This pattern reflects the accumulation of fatigue over consecutive days of training. These findings are consistent with those in Chapter 5, where similar psychological responses did not recover to pre-training levels by the following day. Similarly, BRUMSV ratings showed a significant decline after each training session, reinforcing the cumulative psychological effects induced by the training. In contrast, stress and motivation ratings remained stable, suggesting these variables were either unaffected or recovered to pre-activity levels between sessions. These findings suggest that the orienteering training camp sufficiently imposed psychological load on orienteers.

The delayed recovery observed at 24- and 48-hours post-training aligns with previous research (Russell et al., 2019; Russell et al., 2022; Thompson et al., 2022; Abbott et al., 2020) and the findings in Chapter 5. These results reflect that both simulated orienteering competition training and actual competition can lead to cumulative fatigue, which may negatively affect performance in subsequent sessions or days. The significant increase in motivation from POST4 to 48POST further highlights the occurrence of delayed recovery, possibly reflecting improvements in physical recovery following intense training. Conversely, perceived MF ratings showed a significant decline at 48POST implying that while MF may persist in the short term, full recovery may take longer. These findings emphasise the importance of identifying effective recovery strategies that target both MF and PF to optimise post-training readiness. As previously mentioned, no significant gender effects were observed across any outcome variables, which supports recent meta-regression findings that gender does not significantly influence susceptibility to MF (Habay et al., 2023). The similarity in responses between male and female participants reinforces that similar training and recovery protocols may be appropriate for both genders. This finding demonstrates that gender should not be considered as a primary factor when designing training and recovery interventions for well-trained orienteers.

The results suggest that consecutive days of intensive orienteering training led to increased fatigue and mood disturbances, with delayed recovery reported in psychological variables such as perceived MF and PF. Based on these findings, future research should explore individualized recovery strategies that can reduce the effects of cumulative fatigue and optimize post-training recovery. Furthermore, future investigations with larger sample sizes and more controlled training environments may provide additional insights into potential gender-related differences and help evaluate the effectiveness of specific recovery interventions.

To conclude, the delayed recovery observed in perceived MF highlights the need to identify effective recovery strategies following orienteering training. Considering the potential effects of MF on physical performance as discussed in section 2.2, future research should prioritise interventions that address both the acute and cumulative effects of MF to optimise recovery and enhance performance outcomes. The consistency in responses across male and female participants suggests that standardised training protocols may be appropriate for both genders, with future studies focusing on refining recovery strategies to enhance optimal training adaptation.

6.5 Conclusion

This study demonstrated that simulated orienteering competition training camp imposes psychological demands on national junior orienteers. The progressive accumulation of perceived MF across consecutive days, together with incomplete recovery 48 hours post-training, highlights the importance of structured recovery protocols in orienteering. These findings suggest that psychological recovery should be considered alongside physical fatigue management strategy to optimise athlete readiness. While the observed psychological responses were consistent across participants, the persistence of fatigue and psychological disturbances raises questions about the long-term implications of repeated exposure to intensive training. Future research should explore recovery interventions that specifically target MF and explore their role in supporting both performance and athlete well-being.

Chapter 7. Discussion and Practical applications

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7.1 Restatement of the thesis aims

The overarching aim of this thesis was to improve the understanding of the presence of MF in orienteering and explore the potential effects of MF on orienteer's psychological responses. The first investigation of this thesis (study 1) sought to gather consensus from international orienteering experts on the interpretation and effects of MF in orienteering. Subsequent investigations with junior national to national-level orienteers focused on exploring the presence of MF during orienteering competition (study 2) and simulated orienteering competition training (study 3) to validate the agreement from study 1 and explore the potential effects of MF on psychological responses under different environments. The summary of the findings and limitations of the three studies (studies 1 to 3), as well as directions for future research and practical applications, are discussed below.

7.1.1 Reflection on the Research Approach

At the outset of this research journey, I expected a structured and linear process, with each experimental chapter logically building on the previous one. However, the outbreak of coronavirus during the early stages of my PhD significantly interrupted the timeline, introducing numerous methodological and logistical challenges that extended beyond the experiments themselves. The global pandemic required rapid adaptation, not only for researchers but also across all industries, as we were required to make rapid adjustments to new and unpredictable environments. Like many PhD students in sports science, I had provisioned conducting the research directly with athletes in a controlled laboratory environment. However, due to health and safety restrictions, this became impossible during the early stage of the experiments. Consequently, the experiments were shifted to a remote format, where the focus transitioned to managing environmental variability and maintaining consistency in data collection. In the absence of a controlled laboratory research setting, the priority became maintaining methodological rigour through careful planning and standardisation of protocol and/or procedures, ensuring the reliability and validity of the findings.

A key lesson learned throughout this PhD was the ongoing challenge of balancing ecological validity with methodological rigour. The studies conducted during an orienteering competition (Chapter 5) and a simulated competition training camp (Chapter 6) would have benefited from greater control over the timing of pre- and post-measurements, rather than relying on a 30-minute window. However, restrictions related to event access and participant interaction, particularly under COVID-19 protocols, created obstacles to standardisation and introduced variability into the data. Event cancellations also required the rescheduling of data collection, demanding adaptability and flexibility in study design and methodology. Additionally, pandemic-related travel and contact restrictions shifted the focus of the experiments from UK-based athletes to international elite orienteers. While this expanded the scope of the research, it also introduced challenges including managing time zone differences, accommodating varied training routines and competition schedules, which added complexity not only to the planning and execution of studies but also to the interpretation of the results.

Despite these challenges, this experience has been valuable to my development as an independent researcher. Identifying unforeseen disruptions required strategic problem-solving, adaptability, and an increased sense of autonomy in decision-making. The ability to maintain methodological consistency under these challenges reinforced the importance of clear and standardised protocols while also highlighting the importance of being flexibile when encountering uncertaininty. Ultimately, these experiences will inform my future work, equipping me with a more strategic and resilient approach to conducting research in dynamic and unpredictable environments.

7.2 Summary of experimental findings

It has been widely demonstrated that the MF induced through performing prolonged periods of computerised cognitively demanding tasks can impair the endurance, tactical and decision-making performance of athletes (Habay et al., 2021; Brown et al., 2020; Van Cutsem et al., 2017; Sun et al., 2022). However, the applicability of the existing findings was limited as most investigations have relied on artificial MF protocols that fail to consider individual characteristics or the demands of sport-specific contexts.

Study 1 used a Delphi approach to investigate the development, causes, effects and methods to reduce MF in orienteering by obtaining international orienteering expert consensus. This was the first study to bridge the gap between the existing literature and practitioners' experience, providing insights into how MF is perceived and managed within elite orienteering. The experts reached a consensus that MF is experienced in both orienteering training and competition, but they highlighted potential differences in its severity between orienteering training and competition (section 4.3). Moreover, the experts also emphasised that MF and PF do not necessarily increase simultaneously, but that PF can exacerbate the perception of MF (section 4.3). This underscores the importance of measuring other psychological variables when investigating MF to capture its multifaceted nature. The experts agreed that MF affects the emotional state of the orienteers, suggesting the inclusion of motivation, fatigue and confusion in the measurement of MF. Additionally, they also reached a consensus that the existing definitions of MF do not adequately reflect the experiences of orienteers. Consequently, an orienteering-specific definition of MF was developed and applied in subsequent studies to increase the precision of the discussion and contextual relevance of the research.

Study 2 measured changes in perceived MF and related psychological variables such as PF, motivation and stress before and after orienteering competition in national-level orienteers. The findings in section 5.3 demonstrated that participation in the sprint, middle- or long-distance orienteering competition acutely increased the perceived MF, motivation, PF, BRUMSF and BRUMSC while decreasing motivation, and BRUMSV ratings. Importantly, these effects sustained beyond the competition day, with perceived MF ratings remaining elevated the following day. Additionally, the magnitude of change in MF differed from PF, highlighting these two are different fatigue constructs and should be monitored separately. Regardless of race duration and schedule, neither MF nor PF ratings recovered to pre-competition value even 48 hours after the final competition (section 5.3), reinforcing the impact of orienteering competition and the need for practitioners to monitor MF during multi-day events. In contrast to previous research discussed in sections 2.4.1.1, 2.5.1.1 and 2.5.1.2, this study found no significant impairment in the Stroop task reaction time and response accuracy, even when perceived MF ratings were high. This implies that the Stroop task may lack the sensitivity to detect MF in well-trained orienteers.

Study 3 adopted a similar experimental design as study 2 to investigate the changes in perceived MF and other psychological responses before and after each training day during a 4-day orienteering training camp with national junior orienteers. This study reported a consistent acute increase in perceived MF following each training session regardless of the simulated race type (section 6.3). Specifically, the progressive increase in pre-training MF values during a 4-day orienteering training camp implies incomplete recovery between sessions, reflecting an accumulation of MF over time. This study supports the findings from study 2 that perceived motivation, stress, tiredness and PF were different to MF (section 6.3). Although perceived MF and PF demonstrated similar direction of changes in studies 2 and 3, the different extents and timing of these changes further support the consensus from study 1 that MF and PF do not increase simultaneously (section 4.3). Furthermore, the findings also demonstrate that MF should not be primarily defined as an increased subjective tiredness because the magnitude of changes varied throughout the training camp (see Figures 6.2 and 6.3). Interestingly, perceived motivation increased even when participants reported higher MF, suggesting that MF does not necessarily impair motivation (Figure 6.3). Although the perceived sleep quality was lower during the training camp compared to 24POST and 48POST (section 6.3), this does not appear to reflect insufficient time allocated for rest as displayed in the training schedule in Table 6.1 (section 6.3). This may point to the ineffective use of recovery time rather than a lack of opportunity for rest during the camp.

Taken together, Chapters 5 and 6 demonstrate that both orienteering competition and simulated competition training camp significantly impaired perceived MF and other psychological responses, with changes ranging from moderate to large ES. Importantly, the direction and extent of changes were similar across both contexts, indicating that simulated orienteering competition training camp may serve as a substitute for actual competition in preparing orienteers for the psychological and physical challenges of competition. However, as highlighted by orienteering experts in study 1, it is important to acknowledge that the MF experienced during competition may not be fully replicated in training due to potential differences in mental state (section 4.3, Table 4.2-4.3). While similar patterns of change were observed in studies 2 and 3, it is important to note that studies 3 used a simulated competition training format rather than a traditional orienteering training session. This may influence the perception and experience of MF among well-trained orienteers. Further discussion regarding the potential differences between simulated competition training camp and training is provided in section 7.3.2.3.2. Therefore, the findings should be interpreted with caution and should not be taken as contradictory to the expert consensus reported in study 1, but rather as complementary findings under specific contexts.

Both studies 2 and 3 used random intercept models for the majority of the outcome variables including perceived MF, indicating significant individual variability in psychological responses. This emphasizes the importance of adopting personalised approaches to training and recovery, as orienteers respond differently to both competition and simulated competition environments. Moreover, no significant gender differences were reported in either study, supporting a previous systematic review that gender has minimal impact on susceptibility to MF in well-trained athletes (Habay et al., 2023). Importantly, the inclusion of random intercept models in the supplementary analysis of studies 2 and 3 does not contradict the findings reported through ES analysis. These models support the existence of individual variability in perceived MF and other psychological responses and the need for statistical approaches that account for individual variability. Given the consistent inter-individual variability in both competition and training contexts, it is recommended that personalised recovery strategies be adopted to optimise athlete readiness and orienteering performance.

Across the three studies in this thesis, the findings suggest that although MF and PF show similar direction and magnitude of changes during the orienteering competition (study 2) and training (study 3), key differences were observed in their day-to-day variations (Figure 6.3). In study 3, both PF and MF ratings were measured throughout the 4-day training camp. The 95%CI for PF ratings remained overlapped with the PRE1 values across all days, suggesting a marginal cumulative increase in PF. In contrast, the 95%CI for perceived MF ratings did not overlap with the PRE1 value from POST2 onwards, and the ratings continued to increase each day, demonstrating a progressive accumulation of MF. These findings further support the notion that MF and PF represent different fatigue constructs as reported in similar research (Russell et al., 2019). Although the ratings respond similarly to training and competition in the short term, the changes and underlying mechanisms differ. Recognising these differences is crucial for effective fatigue management. Future research should continue to investigate MF and PF separately to improve our understanding of their respective contributions to fatigue, performance, and recovery in sports.

7.3 Limitations

General limitations applicable to all studies

7.3.1.1 Small sample size

The sample size for studies 1 (n = 24), 2 (n = 16) and 3 (n = 11) were small due to the limited availability of national-level orienteers and practitioners. However, this limitation does not diminish the quality of the research as the research was obtained and conducted with an elite population. This offers meaningful insights into the presence of MF within a high-performance context. These findings contribute to improving our understanding of MF in elite orienteering, highlighting the relevance of perceived psychological responses alongside traditional physiological measures. This provides a foundation for future investigations into performance-limiting factors beyond the physiological domain.

7.3.1.2 Mixed gender sample

Although this thesis was unable to conduct a comprehensive gender comparison due to the small sample size, both elite male and female orienteering athletes were included in the investigations. Therefore, the findings and explanations were not based on one gender only. The supplementary analysis in studies 2 and 3 revealed that gender had minimal effect on the outcome variables, reinforcing that the gender imbalance in the sample is unlikely to have significantly affected the interpretation of results. Moreover, previous research has found no gender differences in the impact of MF on endurance running performance among well-trained runners (Lopes et al., 2020), supporting the notion that gender comparison may be less important when exploring the effects of MF in orienteering.

7.3.1.3 Participation preparation prior to data collection

Studies 2 and 3 of this thesis did not standardise the pre-study nutritional status of the participants, which could be seen as a limitation because the consumption of supplements such as caffeine has been shown to reduce perceived MF (Van Cutsem et al., 2018). However, both studies 2 and 3 utilised an observational design intending to observe natural changes in perceived MF before and after orienteering competition (study 2) and training (study 3). As such, we intentionally avoided implementing a standardised dietary plan to minimise disruption to participant's daily routines, thereby ensuring the ecological validity of self-report ratings. It is reasonable to assume that elite athletes often follow established dietary routine during competition and training camps and are unlikely to consume unfamiliar foods or supplements that are not regularly in their dietary plan.

To reduce potential nutrition-related confounding variables, participants in studies 2 and 3 were advised to complete the pre-competition or pre-training survey within 30 minutes of waking. This timing ensured that responses were likely recorded before any nutrition intake, reducing the possibility that self-report ratings were influenced by food or supplement consumption. While previous research has consistently compared the result of objective physiological measures such as EEG, HR monitoring or other physiological biomarkers to explain the changes in perceived MF (Van Cutsem et al., 2017; Pires et al., 2018; Taya et al., 2017), such method were not feasible in our studies. The geographical location of participants and limited access to equipment made it technically impractical to implement this type of measurement. Importantly, introducing these procedures could have affected participants' competition or training routines, potentially introducing additional confounding variables.

7.3.1.4 Non-orienteering sources of mental fatigue

Previous investigation has highlighted that engaging with social media applications on a smartphone for 30 minutes can induce MF (Fortes et al., 2020; Fortes et al., 2021), and education demands have also been perceived to be one of the potential causes of MF (Thompson et al., 2020). However, this thesis did not record the activities participants completed outside of orienteering, which could have affected their MF ratings. This does not compromise the validity of the results because the primary aim of this thesis was to explore the natural occurrence of MF during and after orienteering activities. All pre-orienteering ratings were recorded within 30 minutes of waking, and post-orienteering ratings were recorded immediately after orienteering activities, minimising the effect of external factors during the measurement windows. It is acknowledged that activities performed after completing the post-orienteering survey were neither controlled nor recorded and may have contributed to increased MF ratings on the next day. Although participants were strongly advised to complete the pre-activity survey within 30 minutes of waking, there remains the possibility that some participants may have engaged in other tasks before completing the survey.

7.3.1.5 Measurement of mental fatigue

This thesis acknowledges that the primary method used to measure MF in studies 2 and 3 was a 0-100mm VAS, which may be susceptible to response bias. Although incorporating objective measurements of MF along with subjective measurements could theoretically offer a more robust evaluation, the validity of objective measurements for MF remains questionable (section 2.5.1). Importantly, MF is defined as a subjective experience, and therefore, subjective measures remain the most appropriate measurement. The 0-100mm VAS is a widely accepted and well-established tool for measuring perceived MF as reported in previous research (Smith et al., 2019). Importantly, the use of VAS in similar observational studies increases the comparability of findings across research (Abbott et al., 2020; Thompson et al., 2020). The appropriateness of using VAS to measure MF has been discussed in section 2.5.2.4. Most importantly, the observed mean changes in MF ratings in our study are consistent with previous findings, reinforcing both the validity of the results and the generalisability of the VAS as a reliable tool for measuring MF.

7.3.1.6 The practical effects of mental fatigue in orienteering

International orienteering experts in study 1 reached a consensus that MF negatively affects orienteering performance, particularly in decision-making speed and accuracy (section 4.3). However, studies 2 and 3 employed an observational design without implementing interventions or orienteering performance-based assessments, and therefore were unable to examine the effects of MF on orienteering performance under different mental states. These studies focused on the changes in perceived MF and other psychological responses during orienteering training and competitions. Consequently, this thesis cannot conclusively determine the practical impact of changes in perceived MF on orienteering performance.

As discussed in sections 5.4 and 6.4, while some overlap in the 95%CIs for MF ratings is present, this does not substantially affect our interpretation. Studies 2 and 3 were observational research, focusing on tracking changes in MF over a training and competition period, rather than aiming for statistical significance at each time point. The primary objective was to observe trends, which are valuable for understanding how MF accumulates during sustained periods of training and competition. Furthermore, we acknowledge the subjective nature of MF, with individual athletes likely experiencing it differently. To account for these individual differences, both mean values and individual MF ratings were included in the analysis, enabling us to observe patterns at both the group and individual levels. This approach facilitates a more nuanced interpretation of MF changes, particularly in high-performance contexts where individual responses may be crucial.

The ES reported in studies 2 and 3 demonstrated a meaningful increase in MF despite the overlap of 95%CIs. The ES offers additional context to the observed trends, emphasising the practical relevance of MF accumulation throughout the training and competition periods. In repeated-measures designs, the overlap of 95%CI is not necessarily a reliable indicator of non-significance due to the paired nature of the data (Payton et al., 2003; Cumming, 2012; Calin-Jageman & Cumming, 2019). As commonly observed in elite athlete research, small sample sizes can introduce variability (Cumming, 2012), which impacts the precision of CIs for subjective measures like perceived MF ratings. While an overlap of 95% CIs may occur, it does not invalidate the reported findings. Thus, the observed ES and trend in MF remain meaningful, consistent with the literature, and practically relevant for athlete management.

While studies 2 and 3 did not directly measure the practical effects of MF on orienteering performance, this thesis draws upon findings from the literature (section 2.2), which indicate that moderate to large changes in perceived MF are likely to negatively impact physical and cognitive performance. It is acknowledged that adopting a generalized threshold such as the ±10 mm on the VAS as a small effect proposed by Hopkins and Rowlands (2024) may underestimate the practical significance of observed changes. Again, MF is a subjective construct influenced by numerous variables, including occupation and daily activities (Fortes, 2020; Thompson, 2019), as supported by orienteering experts in Chapter 4 too (Lam et al., 2020). These factors necessitate a context-specific interpretation of MF changes rather than relying primarily on generalized thresholds.

Furthermore, previousresearch demonstrates that even small changes in MF on VAS can have significant detrimental effects. For example, small effects on VAS for MF negatively impaired decision-making (Fortes et al., 2021; Jacquet et al., 2023), visual search behavior (Fortes et al., 2022), and endurance performance (Fortes et al., 2022). Importantly, even small increases in MF have been shown to hinder training adaptations over periods of 2 to 8 weeks (Fortes et al., 2022). This evidence highlights that context-specific thresholds are necessary for interpreting the practical effects of MF in different settings. This highlights the need for context-specific thresholds when interpreting the practical effects of MF. In high-performance environments, even small changes can have meaningful impacts, emphasizing the importance of nuanced interpretation tailored to the unique demands of the activity or sport.

7.3.1.7 Baseline of the mental fatigue ratings

Rescaling baseline MF VAS ratings could theoretically standardise the starting point and improve the interpretability and accuracy of the findings, as suggested by Hopkins and Rowlands (2024). However, this thesis retained absolute values to maintain consistency with the literature discussed in sections 2.2 and 2.5.2, as MF rarely starts from a uniform baseline. Previous research shows that everyday stressors, such as occupational and academic pressures, contribute to baseline fatigue levels including perceived MF, even without intentional induction (Martin et al., 2019; Thompson et al., 2019). Standardizing data to a fixed baseline may overloop these pre-exisiting variations and mispresent the normal mental states of the participants. Therefore, using absolute values provides a more realistic depiction of MF as experienced in real-world conditions and aligns with established methodological approaches in the field.

7.3.2 Limitations for specific study

7.3.2.1 Study 1

7.3.2.1.1 Location of the participants

The consensus achieved in this study was largely based on the perspectives of European orienteering athletes and practitioners only because the majority of the top-ranked athletes are from European countries as reported on the International Orienteering Federation's website (http://ranking.orienteering.org/?ohow=F). While this thesis attempted to recruit elite athletes and practitioners from other countries, the limited availability of contact details and low response rates restricted broader participation. This resulted in representation from only one expert each from Australia and Canada. Consequently, the potential impact of geographical and/or cultural differences on perceptions and interpretation of MF remains unknown.

7.3.2.1.2 Age range

Although the age of the participants was not recorded in study 1, strict inclusion criteria were employed as displayed in section 3.2. Participants were required to be at least 18 years old and to have a minimum of 10 years of experience in either coaching or competing in orienteering. As this Delphi study aimed to build consensus among orienteering experts on the issues regarding the development of MF in orienteering, rather than comparing outcomes across age groups, age homogeneity was not a prerequisite. Unlike empirical studies where age and maturity may influence data interpretation, the key consideration in the Delphi study was the depth of expertise and experience within the sport. Therefore, age differences between participants are unlikely to have affected the findings. The robustness of the findings is further supported by the three-round Delphi process, which allowed for feedback, reflection and refinement of the consensus.

7.3.2.1.3 Primary role of the participants in orienteering

This thesis acknowledged an imbalance in the representation of orienteering athletes, former athletes and coaches. Most participants identified as athletes or former athletes, raising the concern that the consensus may have leaned towards the athlete's perspective, potentially neglecting the valuable insights from orienteering coaches. However, it was technically difficult for participants to differentiate their roles in orienteering because some orienteering coaches had formerly been professional athletes and were still competing leisurely. Participants identified what best described their current role in orienteering, however, there might be a possibility that they expressed their thoughts from an athlete perspective instead of an orienteering coach. The inability to quantify which perspectives people were using to provide their response was a reason why this study did not analyse the data in separate populations (e.g. coaches vs. athletes). It would have been advantageous if the study had recruited those who had only been coaches and only been athletes in orienteering, but this may not be feasible.

7.3.2.1.4 Validity of the consensus

Despite the withdrawal of five experts after three rounds of the survey, the study maintained a 75% response rate from the original 24 orienteering experts, exceeding the recommended 70% threshold for Delphi studies (Keeney et al., 2011; Price et al., 2020). This high retention rate underscores the study's methodological rigor and enhances the reliability of its findings. Given that the achieved response rate in this study exceeded this benchmark, the dropout of five experts is unlikely to have compromised the conclusions of the study. To elaborate, the consistent engagement of the majority of participants supports the robustness of the consensus reached, reinforcing the credibility of the findings.

7.3.2.1.5 Prior knowledge of mental fatigue of the participants

It is acknowledged that the participants in the Delphi study had extensive experience in orienteering as displayed in section 3.2 and 4.2 but were not experts in MF or MF research. Similar MF investigations with athletes and practitioners also recruited sporting experts who were not MF experts to investigate how elite level populations perceive MF in sports (Russell et al., 2019). This indicates it is unnecessary, and prehaps unrealistic, to require participants to have a strong academic knowledge of MF but rather to have an appropriate expertise in the profession to participate in this Delphi study. Additionally, other Delphi studies have recruited participants with field-specific expertise, though not necessarily with topic-specific knowledge. For example, coaches, athletes, and health educators were recruited to determine the coach's role in promoting athletes' mental health (Bissett et al., 2020). Another study combined recreational to elite-level athletes, sports medicine specialists, and organisational administrators to investigate preventive measures in outdoor sports (Schneider et al., 2024). These examples support the validity of consensus reached by professionals with relevant experience, highlighting that the findings in Chapter 4 are both appropriate and transferable within the profession.

7.3.2.2 Study 2

7.3.2.2.1 Racing schedule

This study included race schedule that ranged from 1 to 4 days and involved different types of orienteering competitions (sprint, middle-, long-distance, relay and KO-sprint). Due to the variation in race types and duration across participants, an in-depth analysis of the day-to-day changes in self-report measurements was not available. However, the pre-and post-competition self-report ratings were combined to provide an overview of changes experienced by orienteers during the competition. Additionally, the ratings recorded immediately after the final orienteering competition were used to analyse the impact of the competition on recovery at 24- and 48 hours post-competition. This approach adequately reflected the ratings of all participants, regardless of the length of their competition. To address this limitation, future research may consider utilising a longitudinal design with the same athletes competing in the same orienteering competition. However, this could also be challenging, as well-trained orienteers often specialise in certain race types and may not compete in all orienteering race types during a tournament. Most importantly, this study was conducted in a field-based setting without control over the race format or environmental conditions, implying that the findings accurately reflect real-world scenarios.

7.3.2.2.2 Different level of competition

All participants in this study were all national-level orienteers, with six ranked top 200 in the world. It is acknowledged that the physical and cognitive demands of the competition may vary depending on the level of the athletes, which could influence the self-report measures. However, the aim of this study was to explore whether orienteers experience MF during the competition. Therefore, we included the competitions that were perceived to be important by the participants such as the selection race for international events and competition for world ranking points. Consequently, it is reasonable to assume that all participants competed with their maximum physical and cognitive effort. As such, the variation in competition type should not have affected the self-report ratings as these competitions were crucial to their careers.

7.3.2.2.3 Unstandardised devices and environment to complete the Stroop-colour task

Following the completion of the self-report measures of the survey, participants completed the Stroop task using the same self-selected electronic devices. As mentioned in section 5.2, there was no standardisation of the electronic devices utilised to complete the survey, meaning the size of the display of the Stroop-colour task could vary between individuals. We acknowledge that no controlled environment was provided for the participants to complete the Stroop task. However, participants were advised to complete the Stroop task on the same electronic device and in an area free from distraction to ensure consistency and minimise variability in responses.

7.3.2.3 Study 3

7.3.2.3.1 Maturation status

The participants in this study were recruited solely from the British Orienteering Talent squad, with the age range of the participants being limited to 15 to 17 years old. As the research was being conducted remotely, the maturation status of the participants was not assessed. This can be seen as a limitation as the participants in this chapter were junior national level orienteers which is different from those in study 2. The aim of this study was not to evaluate the effects of age on MF but to explore the presence of MF during orienteering training. However, a recent meta-regression revealed that age does not significantly affect the MF-susceptibility (Habay et al., 2023). Consequently, the maturation status of the participants is unlikely to influence the results. This study measured the self-report ratings during a 4-day training camp and two days after the camp, offering meaningful findings to the orienteering community on how MF is experienced during competition preparation training camp.

7.3.2.3.2. Physiological load of the training camp

Although the day-to-day variations in self-report ratings during a 4-day training camp were recorded in this chapter, the inclusion of the physiological data of the participants might have enabled a more extensive discussion on the relationship between physical load and the changes in self-report ratings. Nevertheless, the absence of physiological data on the participants should not impose a major limitation on the findings because the MF was assessed subjectively rather than objectively in this study. Additionally, the 4-day simulated orienteering competition training camp was designed to replicate the orienteering competition schedule. However, it is necessary to acknowledge that the training camp could only simulate a competition environment rather than fully replicate actual competition conditions. Participants may have perceived the experience differently compared to a real competition (study 2), potentially influencing the extent and nature of the MF and psychological responses observed. Importantly, the physiological load of the participants was not measured due to the limited access to the standardised physiological monitoring equipment for national junior orienteers.

7.4 Future research directions and practical applications

7.4.1 Future research directions

This thesis has contributed to a better understanding of the occurrence of MF within elite orienteering. Although MF has been described as a psychobiological state that results in an elevated subjective feeling of tiredness (Van Cutsem et al., 2017; Habay et al., 2021), studies 2 and 3 identified the presence of MF through self-report measures and demonstrated changes in perceived MF during orienteering activities. The primary aim of this thesis was to explore the presence of MF among the elite orienteering population. Future investigations should consider employing similar methodology in other sports to examine the natural occurrence of MF in ecologically valid settings. Such an approach would increase the transferability of the findings and reduce the reliance on laboratory-based investigation that usually lacks ecological validity.

Although study 2 investigated the physical demand of orienteering competition among national-level orienteers, the analysis was limited due to the malfunctions in the monitoring devices, limiting the ability to assess the direct effect of MF on the running distance of national-level orienteers. Furthermore, this study did not provide sufficient evidence to evaluate the effect of MF on orienteering-specific performance such as decision-making errors, time taken for navigation or route selection. Future research should aim to investigate how changes in perceived MF affect sport-specific performance, particularly in reaction time and accuracy of the decision-making during orienteering activities. Moreover, it would be valuable to explore the extent to which MF impairs orienteering performance and to determine the performance variables most susceptible to deterioration under mentally fatigued state.

The findings from studies 2 and 3 highlight the need for further investigation into the recovery timeline following MF elicited by orienteering competition and training. Future research should pay attention to multiple days of racing or training as study 3 provides compelling evidence that perceived MF can accumulate over multiple consecutive days of intense orienteering training. Further research should consider implementing longitudinal research designs involving specific sports populations to monitor day-to-day psychological responses during training and competition periods. This approach would facilitate a greater understanding of acute and cumulative MF and allow for differentiation between their respective effects on performance and recovery. This provides vital information to the practitioners to decide whether MF should be minimised to the greatest extent through effective fatigue management.

7.4.2 Practical applications

This thesis utilised an ecologically valid approach to investigate the presence of MF within orienteering. The key practical applications of this thesis are summarised as follows:

- It is important to recognise that MF is a common subjective fatigue experience among elite orienteers during both orienteering training and competition. Coaches and athletes should be aware that the orienteering performance could be influenced by the MF elicited during orienteering activities.
- Orienteering athletes and practitioners should note that MF can increase acutely and sustain up to 48 hours after participating in orienteering events regardless of the race distance. It is advised to allocate sufficient recovery time to recover from the increased MF and to avoid scheduling multiple races within a short period of time.
- The development of MF can be both acute and cumulative, suggesting practitioners adjust the training based on the ratings to prevent excessive accumulation of MF, particularly MF can remain elevated for at least 24 hours following intense orienteering training.
- It would be beneficial to record the ratings of MF alongside PF, tiredness, BRUMS vigour, fatigue and confusion to provide a comprehensive overview of the psychological state of orienteers.
- Fatigue management for well-trained orienteers should be tailored to the individual, as responses to fatigue vary, with gender having minimal impact on the development of such strategies.

7.5 Conclusions

This thesis demonstrates that both experienced orienteering athletes and practitioners recognise the occurrence of MF during orienteering competitions and training. Subsequent studies in this thesis show that perceived MF increases acutely to a moderate to large extent during orienteering competition and training. Although MF is a different construct from other psychological variables that require specific attention and management, the inclusion of additional psychological variables may enhance the understanding of its presence and influence of MF. Additionally, this thesis also highlights the delayed recovery from elevated MF experienced during orienteering training and competition with a small to moderate increase in perceived MF ratings persisting for at least 48 hours post-orienteering competition and training, compared to the ratings before the first session of orienteering training and competition.

By adopting an ecological approach in the investigation such as utilising observational research methods during a real-world orienteering competition and simulated orienteering competition training camp, this thesis reduces the reliance on artificial MF protocols, offering more realistic insights for understanding MF in orienteering. This thesis provides the foundation for further research into the impact of MF on orienteering performance, particularly over multiple days of training and/or competition. The observed acute increase in perceived MF following orienteering competitions and its progressive increase during multiple days of orienteering training demonstrates the inevitability of MF in orienteering. This underscores the importance of investigating effective management strategies to enhance recovery and optimise orienteers' performance.

Another key finding from this thesis is the significant individual variability in responses observed in both competition and simulated competition training camp contexts, highlighting the need for individualised training and recovery strategies. Additionally, the findings further indicate that gender has minimal impact on susceptibility to MF in well-trained orienteers, which is consistent with the literature. This reinforces the importance of individualising the training and recovery management rather than relying on demographic factors only.

It is important to acknowledge that this thesis focused on the elite orienteering population for the investigation, where different training histories of the individuals may affect the amount of MF they experienced during orienteering activities as reported by international orienteering experts. This thesis has significantly advanced our understanding of MF in orienteering, particularly in terms of interpretation of MF from the perspectives of orienteering athletes and practitioners, acknowledging the presence of MF during orienteering competition and training, and recognising the potential differences between MF and other psychological responses. Considering that orienteering fundamentally requires a substantial amount of physical and cognitive output, the presence of MF could potentially have a negative effect on this sport. Therefore, the continued investigation of MF in orienteering is crucial.

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Appendices

Appendix A – Ethics Approval

Appendix A1 - Ethics Approval Letter for Chapter 4 - Study 1 (Ref: NL22102020-1)

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Ref: NL22102020-1

Nicholas Lam
Moray House School of Education and Sport

Date: 5th February 2021

Dear Nicholas,

Title: The Development of Mental Fatigue in Orienteering: A Delphi Study

The School of Education and Sport Ethics Sub-Committee has now considered your request for ethical approval for the studies detailed in the above application.

This is to confirm that the Sub-Committee is happy to approve your application and that the research meets the School Ethics Approval criterion for this particular project. A standard condition of this ethical approval is that should any amendment, or deviation from the original protocol outlined in your application need to be made to carry out or continue your research, please notify the Ethics Sub-Committee at MHSES-Ethics@ed.ac.uk

The Committee also needs to be notified if there are any unexpected results or events once the research is underway that raise questions about the safety of the research.

Should you receive any formal complaints relating to the study you should notify the MHSE Ethics Committee immediately by email to MHSES-Ethics@ed.ac.uk

Yours sincerely

On behalf of:
Dr Fiona O'Hanlon
Convener, School Ethics Sub-Committee

Appendix A2.1 - Ethics Approval Letter for Chapter 5 - Study 2 (Ref: NLAM09032022)

THE UNIVERSITY *of* EDINBURGH
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Ref: NLAM09032022

Nicholas LAM
Moray House School of Education and Sport

Date: 1th April 2022

Dear Nicholas,

Title: Investigation on the Development of Mental Fatigue in Orienteering

The School of Education and Sport Ethics Sub-Committee has now considered your request for ethical approval for the studies detailed in the above application.

This is to confirm that the Sub-Committee is happy to approve your application and that the research meets the School Ethics Approval criterion for this particular project. A standard condition of this ethical approval is that should any amendment, or deviation from the original protocol outlined in your application need to be made to carry out or continue your research, please notify the Ethics Sub-Committee at MHSES-Ethics@ed.ac.uk

The Committee also needs to be notified if there are any unexpected results or events once the research is underway that raise questions about the safety of the research.

Should you receive any formal complaints relating to the study you should notify the MHSE Ethics Committee immediately by email to MHSES-Ethics@ed.ac.uk

Yours sincerely,

On behalf of:
Dr Fiona O'Hanlon
Director of Ethics

Appendix A2.2 - Ethics Approval Letter for Chapter 5 - Study 2 - Amendment (Ref: NLAM15042022)

THE UNIVERSITY *of* EDINBURGH
Moray House School of Education and Sport

Research, Knowledge Exchange and Impact Office
Moray House School of Education and Sport
The University of Edinburgh
Old Moray House
Holyrood Road
Edinburgh EH8 8AQ

D/D +44 (0)131 651 4846
S/B +44 (0)131 650 1000

www.ed.ac.uk

Ref: NLAM15042022 - Amendment

Nicholas LAM
Moray House School of Education and Sport

Date: 15th April 2022

Dear Nicholas,

Title: Investigation on the Development of Mental Fatigue in Orienteering

The School of Education and Sport Ethics Sub-Committee has now considered your request for ethical approval for the studies detailed in the above application.

This is to confirm that the Sub-Committee is happy to approve your application and amendment submitted in April 2022 and that the research meets the School Ethics Approval criterion for this particular project. A standard condition of this ethical approval is that should any amendment, or deviation from the original protocol outlined in your application need to be made to carry out or continue your research, please notify the Ethics Sub-Committee at MHSES-Ethics@ed.ac.uk

The Committee also needs to be notified if there are any unexpected results or events once the research is underway that raise questions about the safety of the research.

Should you receive any formal complaints relating to the study you should notify the MHSE Ethics Committee immediately by email to MHSES-Ethics@ed.ac.uk

Yours sincerely,

On behalf of:
Dr Fiona O'Hanlon
Director of Ethics

Appendix A3.1 - Sponsorship Approval Letter for Chapter 6 - Study 3 (Ref: CAHSS2301/10)

University of Edinburgh
College of Arts, Humanities and Social Sciences
Research Governance Office
55 George Square
Edinburgh
EH8 9JU

9th February 2023

Nicholas Lam
c/o Moray House School of Education
and Sport
University of Edinburgh

Dear Nicholas

Study Title:	Investigation on the Development of Mental Fatigue in Orienteering Training
Sponsor number:	CAHSS 2301/10

Under the requirements of the UK policy framework for health and social care research, the University of Edinburgh agrees in principle to act as Sponsor for this project. Sponsorship is subject to you obtaining institutional ethics for the project.

As Chief Investigator, you must ensure that the study does not commence until all applicable approvals have been obtained. Following receipt of all relevant approvals, you should ensure that any amendments to the project are notified to the Sponsor (including an extension to the study end date). Please note that there is a requirement to notify the sponsor once the study has ended.

Yours sincerely

Matt Erikson
Research Governance Coordinator

Sponsorship letter template V2 02Mar22

Appendix A3.2 - Ethics Approval Letter for Chapter 6 - Study 3 (Ref: NLAM15042022J23)

THE UNIVERSITY of EDINBURGH
Moray House School of Education and Sport

Research, Knowledge Exchange and Impact Office
Moray House School of Education and Sport
The University of Edinburgh
Old Moray House
Holyrood Road
Edinburgh EH8 8AQ

D/D +44 (0)131 651 4846
S/B +44 (0)131 650 1000

www.ed.ac.uk

Ref: NLAM15042022J23

Nicholas Lam
Moray House School of Education and Sport

Date: 8th March 2023

Dear Nicholas,

Title: Investigation on the Development of Mental Fatigue in Orienteering Training

The School of Education and Sport Ethics Sub-Committee has now considered your request for ethical approval for the studies detailed in the above application.

This is to confirm that the Sub-Committee is happy to approve your application and that the research meets the School Ethics Approval criterion for this particular project. A standard condition of this ethical approval is that should any amendment, or deviation from the original protocol outlined in your application need to be made to carry out or continue your research, please notify the Ethics Sub-Committee at MHSES-Ethics@ed.ac.uk. The Committee also needs to be notified if there are any unexpected results or events once the research is underway that raise questions about the safety of the research.

If your research involves in-person research, please send your Covid Checklist form and information/consent sheets with the relevant Covid statements (in Appendix 1 of the Covid checklist) to your Head of Institute for consideration and approval. You should also include any other required documents, such as a Travel risk assessment form. The Covid checklist, and associated travel documents, can be found at this link.

Should you receive any formal complaints relating to the study you should notify the MHSES Ethics Committee immediately by email to MHSES-Ethics@ed.ac.uk

Yours sincerely,

On behalf of:
Dr Fiona O'Hanlon
Director of Ethics

Appendix B – Participant Information Sheet for Study 1 – 3

Appendix B1. Study 1

PARTICIPANT INFORMATION SHEET

You are being invited to take part in research on the Development of Mental Fatigue in Orienteering: A Delphi Study (Ref: NL22102020-1). Nicholas Lam, a Doctoral candidate at the University of Edinburgh is leading this research. Before you decide to take part, it is important you understand why the research is being conducted and what it will involve. Please take time to read the following information carefully.

WHAT IS THE PURPOSE OF THE STUDY?

The purpose of the study is to summarise experienced orienteering athletes and coaches opinions about the development of mental fatigue in orienteering to establish a standardised definition for mental fatigue.

WHY HAVE I BEEN INVITED TO TAKE PART?

You are invited to participate in this study because you are an experienced orienteering athlete/ coach.

DO I HAVE TO TAKE PART?

Your participation in this study is entirely voluntary. If you do decide to take part, please keep this Information Sheet and complete the Informed Consent Form to show that you understand your rights in relation to the research and that you are happy to participate. If you do decide to take part, you are still free to withdraw at any time and without giving a reason.

WHAT WILL HAPPEN IF I DECIDE TO TAKE PART?

There will be at least three rounds of surveys. You will be asked a number of questions regarding 1) the definition of mental fatigue, 2) the development of mental fatigue, 3) the cause of mental fatigue, 4) the impacts of mental fatigue in orienteering, and 5) the methods of reducing mental fatigue in orienteering. You will be asked to rate your experience on a numeric scale (0-4) and explain your answer in the designated area. You will be given approximately two weeks to complete each survey. As stated above, this study will emphasis on gaining consensus between experts. Therefore, the second and third survey round will present a summarized finding from the previous round; however, a fourth round of survey may be added if necessary. The survey will be sent to your provided email address; you can complete it online at a time that is convenient for you. The survey should take around 20 minutes to complete. It is highly recommended to complete the survey in one single session. In case you need more time to consider your answer, you can either press skip ' Next ' at the top right corner or press ' Finish Later ' at the bottom of the page. However, please make sure that you have completed all questions before submission.

WHAT ARE THE POSSIBLE BENEFITS OF TAKING PART?

Mentally fatigued individuals are likely to disengage from the task earlier without being physically tired. By sharing your experiences with us, you will improve our understanding of mental fatigue and assist orienteers in performing optimally.

ARE THERE ANY RISKS ASSOCIATED WITH TAKING PART?

There are no significant risks associated with participation.

WHAT IF I WANT TO WITHDRAW FROM THE STUDY?

Agreeing to participate in this project does not oblige you to remain in the study nor have any further obligation to this study. If, at any stage, you no longer want to be part of the study, please inform Nicholas Lam ( ). You should note that your data may be used in the production of formal research outputs (e.g. journal articles, conference papers, theses and reports) prior to your withdrawal and so you are advised to contact the research team at the earliest opportunity should you wish to withdraw from the study. On specific request we will destroy all your identifiable answers, but we will need to use the data collected prior to your withdrawal, and to maintain our records of your consenting participation.

DATA PROTECTION AND CONFIDENTIALITY

Your data will be processed in accordance with the Data Protection Law. All information collected about you (email address, nationality, training/coaching history in orienteering) will be kept strictly confidential. Your data will be referred to by a unique participant number rather than by name. The raw data will only be viewed by the lead researcher - Nicholas Lam, and his supervisory team: Dr Shaun Phillips, Professor John Sproule and Dr Tony Turner. All electronic data will be stored on a password-protected computer file and all paper records will be stored in a locked filing cabinet. Your consent information will be kept separately from your responses in order to minimise risk.

WHAT WILL HAPPEN WITH THE RESULTS OF THIS STUDY?

The results of this study may be summarised in published articles, reports and presentations. Quotes or key findings will always be made anonymous in any formal outputs unless we have your prior and explicit written permission to attribute them to you by name. Information may also be kept for future research.

WHO CAN I CONTACT?

If you have any further questions about the study, please contact the lead researcher, Nicholas Lam ( ).

If you wish to make a complaint about the study, please contact Dr Shaun Phillips ( ).

In your communication, please provide the study title and detail the nature of your complaint.

For general information about how we use your data go to:

https://www.ed.ac.uk/records-management/privacy-notice-research

Appendix B2.1. Study 2 (Online-based participants)

THE UNIVERSITY of EDINBURGH

PARTICIPANT INFORMATION SHEET

You are being invited to take part in research on mental fatigue in orienteering. Nicholas Lam, a PhD student at the University of Edinburgh is leading this research. Before you decide to take part, it is important you understand why the research is being conducted and what it will involve. This study is approved by the Research Ethics Committee of the University of Edinburgh (Ref: NLAM09032022). Please take time to read the following information carefully.

WHAT IS THE PURPOSE OF THE STUDY?

We are investigating whether or not orienteering athletes experience mental fatigue during competitions.

WHY HAVE I BEEN INVITED TO TAKE PART?

You have been invited to take part in this study because you are an orienteering athlete, and you have fulfilled the following criteria: (1) have received a club and/or national level orienteering training; (2) have represented once as a club and/or national team athlete in an orienteering competition; (3) have the ability to read and write in English fluently; and (4) have reached the age of 14.

DO I HAVE TO TAKE PART?

Your participation in this study is entirely voluntary. If you do decide to take part, please keep this Information Sheet and complete the Informed Consent Form to show that you understand your rights in relation to the research and that you are happy to participate. If you are below the age of 18, please complete the parental consent form too. If you do decide to take part, you are still free to withdraw at any time and without giving a reason.

WHAT WILL HAPPEN IF I DECIDE TO TAKE PART?

You will be asked to complete a survey via Qualtrics (an online survey system) on your electronic device (e.g tablet, smartphone or laptop) at various times on each day of your competition period. For example, if you are competing in a **3-day** event, you will complete the survey:

1. Pre-competition day (within 30 mins of waking up in the morning)
2. Competition day 1 (within 30 mins of waking & within 30 mins after the comp)
3. Competition day 2 (within 30 mins of waking & within 30 mins after the comp)
4. Competition day 3 (within 30 mins of waking & within 30 mins after the comp)
5. Post-competition day 1 (within 30 mins of waking)
6. Post-competition day 2 (within 30 mins of waking)

The whole survey (part A – D) should take **no more than 10 minutes** to complete. A reminder text messages will be sent via WhatsApp.

There are four parts in the survey:

Part A

Here, we will collect your age, height, body weight, gender and years of experience in orienteering.

Appendix B2.1. Study 2 (Continued)

Mental Fatigue in Orienteering, Version 3, 30/03/2022

Part B and C

Here, we will ask you to rate your fatigue, stress, motivation, sleep quality and mood. There are four types of survey scales:

1) Numeric scale, where you select the one number that applies to you:

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

2) Visual analogue scale, where you slide the bar on the horizontal line:

3) Multiple-choice questions:

Gender

- Male
- Female
- Prefer not to say

4) Open-ended questions:

How many years have you been competing in orienteering?

Part D

Colour matching task, please complete this part in a place where you won't be disturbed. You will see colour names (**red, green, blue, yellow**) in different 'print' colours. You need to respond to the print colour instead of the meaning of the word by selecting the appropriate box. However, if you see the word 'RED' printed in red colour. The correct answer is red. There are a total of 30 trials in this colour matching task, your response time and accuracy will be recorded. This part will take no more than 5 mins to complete. Please respond as quickly as possible.

Besides, we would like to access the heart rate and global positioning system (GPS) data from your smartwatch, if you wear one while orienteering competition, which allow us to describe the demands of your run. Please submit your data (heart rate and GPS) to once you have completed the competition.

The research project will take place at **two** competition weekends (one familiarization trial and one experimental trial). However, you will receive an email before each race asking if you are still happy to participate.

<u>**WHAT ARE THE POSSIBLE BENEFITS OF TAKING PART?**</u>

Appendix B2.1. Study 2 (Continued)

There are no immediate benefits for your participation in this study. However, doing research like this can enable us to provide you with some useful information to reduce any changes in mental fatigue that might impair your orienteering performance. Your data will be summarised, and you will be informed the outcomes of the study as part of the debrief. However, quotes or key findings will always be made anonymous.

<u>ARE THERE ANY RISKS ASSOCIATED WITH TAKING PART?</u>

There are no significant risks associated with participation.

<u>WHAT IF I WANT TO WITHDRAW FROM THE STUDY?</u>

Agreeing to participate in this project does not oblige you to remain in the study nor have any further obligation to this study. If, at any stage, you no longer want to be part of the study, please inform Nicholas Lam ( ). You should note that your data may be used in the production of formal research outputs (e.g. journal articles, conference papers, theses and reports) prior to your withdrawal and so you are advised to contact the research team at the earliest opportunity should you wish to withdraw from the study. On specific request we will destroy all your identifiable answers, but we will need to use the data collected prior to your withdrawal, and to maintain our records of your consenting participation.

<u>DATA PROTECTION AND CONFIDENTIALITY</u>

Your data will be processed in accordance with the Data Protection Law. All information collected about you (age, gender, email address, training history in orienteering and performance data) will be kept strictly confidential. Your data will be referred to by a unique participant number rather than by name. The raw data will only be viewed by the lead researcher - Nicholas Lam, and his supervisory team: Dr Shaun Phillips, Professor John Sproule and Dr Tony Turner. All electronic data will be stored on a password-protected computer file and all paper records will be stored in a locked filing cabinet. Your consent information will be kept separately from your responses in order to minimise risk.

<u>WHAT WILL HAPPEN WITH THE RESULTS OF THIS STUDY?</u>

The results of this study may be summarised in published articles, reports and presentations. Quotes or key findings will always be made anonymous in any formal outputs unless we have your prior and explicit written permission to attribute them to you by name. Information may also be kept for future research.

<u>WHO CAN I CONTACT?</u>

If you have any further questions about the study, please contact the lead researcher, Nicholas Lam ( ).

If you wish to make a complaint about the study, please contact Dr Shaun Phillips ( ).

In your communication, please provide the study title and detail the nature of your complaint.

For general information about how we use your data go to:

Appendix B2.1. Study 2 (Continued)

https://www.ed.ac.uk/records-management/privacy-notice-research

Appendix B2.2 Study 2– Amendment

THE UNIVERSITY of EDINBURGH

PARTICIPANT INFORMATION SHEET

You are being invited to take part in research on mental fatigue in orienteering. Nicholas Lam, a PhD student at the University of Edinburgh is leading this research. Before you decide to take part, it is important you understand why the research is being conducted and what it will involve. This study is approved by the Research Ethics Committee of the University of Edinburgh (Ref: NLAM15042022). Please take time to read the following information carefully.

WHAT IS THE PURPOSE OF THE STUDY?

We are investigating whether or not orienteering athletes experience mental fatigue during competitions.

WHY HAVE I BEEN INVITED TO TAKE PART?

You have been invited to take part in this study because you are an orienteering athlete, and you have fulfilled the following criteria: (1) have received a club and/or national level orienteering training; (2) have represented once as a club and/or national team athlete in an orienteering competition; (3) have the ability to read and write in English fluently; and (4) have reached the age of 14.

DO I HAVE TO TAKE PART?

Your participation in this study is entirely voluntary. If you do decide to take part, please keep this Information Sheet and complete the Informed Consent Form to show that you understand your rights in relation to the research and that you are happy to participate. If you are below the age of 18, please complete the parental consent form too. If you do decide to take part, you are still free to withdraw at any time and without giving a reason.

WHAT WILL HAPPEN IF I DECIDE TO TAKE PART?

You will be asked to complete a survey via Qualtrics (an online survey system) on your electronic device (e.g tablet, smartphone or laptop) at various times on each day of your competition period. For example, if you are competing in a **3-day** event, you will complete the survey:

1. Pre-competition day (within 30 mins of waking up in the morning)
2. Competition day 1 (within 30 mins of waking & within 30 mins after the comp)
3. Competition day 2 (within 30 mins of waking & within 30 mins after the comp)
4. Competition day 3 (within 30 mins of waking & within 30 mins after the comp)
5. Post-competition day 1 (within 30 mins of waking)
6. Post-competition day 2 (within 30 mins of waking)

The whole survey (part A – D) should take **no more than 10 minutes** to complete. A reminder text messages will be sent via WhatsApp.

There are four parts in the survey:

Part A

Here, we will collect your age, height, body weight, gender and years of experience in orienteering.

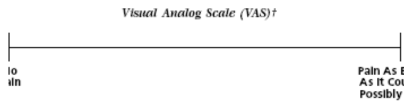
Part B and C

Here, we will ask you to rate your fatigue, stress, motivation, sleep quality and mood. There are four types of survey scales:

1) Numeric scale, where you select the one number that applies to you:

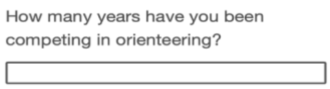
not at all	a little	moderately	quite a bit	extremely
0	1	2	3	4

2) Visual analogue scale, where you slide the bar on the horizontal line:



3) Multiple-choice questions:

4) Open-ended questions:



Part D

Colour matching task, please complete this part in a place where you won't be disturbed. You will see colour names (**red, green, blue, yellow**) in different 'print' colours. You need to respond to the print colour instead of the meaning of the word by selecting the appropriate box. However, if you see the word 'RED' printed in red colour. The correct answer is red. There are a total of 30 trials in this colour matching task, your response time and accuracy will be recorded. This part will take no more than 5 mins to complete. Please respond as quickly as possible.

Besides, we would like to access the heart rate and global positioning system (GPS) data from your smartwatch, if you wear one while orienteering competition, which allow us to describe the demands of your run. Please submit your data (heart rate and GPS) to once you have completed the competition.

The research project will take place at **two** competition weekends (one familiarization trial and one experimental trial). However, you will receive an email before each race asking if you are still happy to participate.

<u>WHAT ARE THE POSSIBLE BENEFITS OF TAKING PART?</u>

There are no immediate benefits for your participation in this study. However, doing research like this can enable us to provide you with some useful information to reduce any changes in mental fatigue that might impair your orienteering performance. Your data will be summarised, and you will be informed the outcomes of the study as part of the debrief. However, quotes or key findings will always be made anonymous.

ARE THERE ANY RISKS ASSOCIATED WITH TAKING PART?

There are no significant risks associated with participation.

RISK OF PARTICIPATION (COVID-19)

We have taken specific steps to minimise the risk of exposure to COVID-19 during the study by adhering to the most up to date Scottish Government guidance (or local equivalent – add detail) These measures include good hand hygiene and surface cleaning, good ventilation, keeping a safe distance, and continued requirement for face coverings in indoor public places. Further, you will only interact with researchers *who in the last 24 hours have had a recent negative lateral flow test* (edit as appropriate), have not experienced COVID-19-related symptoms, and are not required to self-isolate due to close contact with a COVID-19 positive individual.

However, even with these control measures, there remains some additional risk of exposure to COVID-19 from participating in this study, but we do not assess that this risk is higher than engaging in other day-to-day activities.

UNDERSTANDING YOUR RISK FROM EXPOSURE TO COVID-19

It is not possible to eliminate all risk of exposure to COVID-19, and so it is important for you to understand and consider your own personal risk in the unlikely event of exposure.

You may be more likely to be at high-risk from infection if you have previously been advised to shield from the virus, if you have certain health conditions (including heart disease, lung disease, kidney disease, diabetes, or neurological disease), or if you are taking immunosuppressant medication or steroids. The risks of serious consequences from COVID-19 are also known to increase on average with age. To understand more about potential risk factors, please visit this NHS webpage.

MAKING AN INFORMED CHOICE

It is important that you make an informed choice whether or not to take part in this research, considering your potential risk from the virus, and the measures in place to reduce the risk of exposure. It is important that you feel that you have all of the information required regarding these risks, and can consider that in light of your personal circumstances (e.g. health, caring responsibilities). You should have had a chance to reflect on these risks, and discuss them with a researcher (researchers to determine if required), prior to agreeing to participate in the study.

STORING CONTACT DETAILS (ON-CAMPUS)

Appendix B2.2 Study 2 – Amendment (Continued)

If the research requires you to be a visitor in our University Buildings, then for the purpose of NHS Test and Protect we will request your name and contact details and store these for 21 days after the research interaction. If during this 21 day period, the researcher(s) has a positive COVID-19 test then your contact details will be shared with NHS contact tracers who will then decide if they will contact you. These details will not be used for any other purpose or passed to any other third parties. The period of 21 days will ensure full cover of the typical incubation period and additional time during which people may be infectious, to allow for testing and contact tracing. This information is in addition to the data collected as part of the research study, will be stored separately from the research data (researcher add in local arrangements), shared with NHS Test and Protect if requested, and the legal basis for collecting these data is substantial public interest. Further details of the University's Data Protection policies and contacts for the Data Protection Officer can be found at: https://www.ed.ac.uk/data-protection/notice.

STORING CONTACT DETAILS (OFF-CAMPUS)

If the research requires you to be in contact with the research team in an indoor space out with our University campus, then you may be required to provide your name and contact details to the managers of that space. If there is no requirement by the managers of that space to provide such information, then for the purpose of NHS Test and Protect (or local equivalent) we will request and store your name and contact details for 21 days after the research interaction. If during this 21 day period, the researcher(s) has a positive COVID-19 test then, if requested, your contact details will be shared with NHS contact tracers, who may then contact you directly. The period of 21 days will ensure full cover of the typical incubation period and additional time during which people may be infectious. This information relating to your name and contact details is in addition to the data collected as part of the research study, will be stored separately from the research data (researcher add in local arrangements), shared with NHS Test and Protect if requested, and the legal basis for collecting these data is substantial public interest.

WHAT IF I AM UNWELL PRIOR TO THE RESEARCH INTERACTION?

If you feel unwell, experience COVID-19 related symptoms, have a positive lateral flow or PCR test, or have been required to self-isolated due to contact with a COVID-19 positive individual 24 hours before the meeting, then please contact the researcher Nicholas Lam via email or phone +44 7577 447746, and we will postpone or cancel the research interaction.

What if I become unwell after the research interaction?

If you experience COVID-19 related symptoms, and/or have a positive COVID-19 test following the research interaction, please follow the Scottish Government guidance (or local equivalent).

Appendix B2.2 Study 2 – Amendment (Continued)

WHAT IF I WANT TO WITHDRAW FROM THE STUDY?

Agreeing to participate in this project does not oblige you to remain in the study nor have any further obligation to this study. If, at any stage, you no longer want to be part of the study, please inform Nicholas Lam ( ). You should note that your data may be used in the production of formal research outputs (e.g. journal articles, conference papers, theses and reports) prior to your withdrawal and so you are advised to contact the research team at the earliest opportunity should you wish to withdraw from the study. On specific request we will destroy all your identifiable answers, but we will need to use the data collected prior to your withdrawal, and to maintain our records of your consenting participation.

DATA PROTECTION AND CONFIDENTIALITY

Your data will be processed in accordance with the Data Protection Law. All information collected about you (age, gender, email address, training history in orienteering and performance data) will be kept strictly confidential. Your data will be referred to by a unique participant number rather than by name. The raw data will only be viewed by the lead researcher - Nicholas Lam, and his supervisory team: Dr Shaun Phillips, Professor John Sproule and Dr Tony Turner. All electronic data will be stored on a password-protected computer file and all paper records will be stored in a locked filing cabinet. Your consent information will be kept separately from your responses in order to minimise risk.

WHAT WILL HAPPEN WITH THE RESULTS OF THIS STUDY?

The results of this study may be summarised in published articles, reports and presentations. Quotes or key findings will always be made anonymous in any formal outputs unless we have your prior and explicit written permission to attribute them to you by name. Information may also be kept for future research.

WHO CAN I CONTACT?

If you have any further questions about the study, please contact the lead researcher, Nicholas Lam ( ).

If you wish to make a complaint about the study, please contact Dr Shaun Phillips ( ).

In your communication, please provide the study title and detail the nature of your complaint.

For general information about how we use your data go to:

https://www.ed.ac.uk/records-management/privacy-notice-research

THE UNIVERSITY of EDINBURGH

PARTICIPANT INFORMATION SHEET

You are invited to participate in a research study on mental fatigue in orienteering, conducted by Nicholas Lam, a PhD student at the University of Edinburgh. Before deciding whether to take part, it is important for you to understand the purpose of the research and what it will involve. The study has been approved by the Research Ethics Committee of the University of Edinburgh (Ref: NLAM15042022J23). Please ensure that you take the time to read the following information carefully.

WHAT IS THE PURPOSE OF THE STUDY?

We are looking into whether orienteering athletes experience mental fatigue during orienteering training.

WHY HAVE I BEEN INVITED TO TAKE PART?

You have been invited to take part in this study because you are an orienteering athlete, and you have fulfilled the following criteria: (1) have received national level orienteering training; (2) have the ability to read and write in English fluently.

DO I HAVE TO TAKE PART?

Your participation in this study is entirely voluntary. If you do decide to take part, please keep this Information Sheet and complete the Informed Consent Form to show that you understand your rights in relation to the research and that you are happy to participate. If you are below the age of 18, please pass the parental information sheet and parental consent form to the relevant parent/guardian. Deciding not to take part or withdrawing from the study will not affect your rights in any way.

WHAT WILL HAPPEN IF I DECIDE TO TAKE PART?

You will be asked to complete a survey via Qualtrics (an online survey system) on your electronic device (e.g. tablet, laptop, or smartphone) at different time points throughout your training. For instance, if you are taking part in a 3-day training camp, you will need to submit the survey at the following times:

1. Training day 1 (within 30 mins of waking & within 30 mins after the training)
2. Training day 2 (within 30 mins of waking & within 30 mins after the training)
3. Training day 3 (within 30 mins of waking & within 30 mins after the training)
4. Post-training day 1 (within 30 mins of waking)
5. Post-training day 2 (within 30 mins of waking)

Each survey (part A – D) should take **no more than 5 minutes** to complete. A reminder text messages will be sent via email.

There are four parts in the survey:

Part A

This part will collect your age, height, body weight, gender and years of experience in orienteering.

Parts B, C and D

Mental Fatigue in Orienteering Training, Version 2, 27/02/2023

THE UNIVERSITY of EDINBURGH

Here, we will ask you to rate your fatigue, stress, motivation, sleep quality and mood. There are four types of survey scales:

1) Numeric scale, where you select the one number that applies to you:

Version 1:

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

Version 2:

0	1	2	3	4	5	6
○	○	○	○	○	○	○

2) Visual analogue scale, where you slide the bar on the horizontal line:

3) Multiple-choice questions:

Gender

Male

Female

Prefer not to say

4) Open-ended questions:

How many years have you been competing in orienteering?

The research project will take place at **one training camp** over several days**.** You can complete the sample survey in your own time to get familiar with the survey before proceeding to the training camp.

<u>WHAT ARE THE POSSIBLE BENEFITS OF TAKING PART?</u>

There are no immediate benefits to your participation in this study. However, doing research like this can enable us to provide you with some useful information to reduce any changes in mental fatigue that might impair your orienteering performance. Your data will be summarised, and you will be informed of the outcomes of the study as part of the debrief. However, quotes or key findings will always be made anonymous.

Appendix B3. Study 3 (Continued)

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ARE THERE ANY RISKS ASSOCIATED WITH TAKING PART?

There are no significant risks associated with participation.

WHAT IF I WANT TO WITHDRAW FROM THE STUDY?

Agreeing to participate in this project does not oblige you to remain in the study nor have any further obligation to this study. If, at any stage, you no longer want to be part of the study, please inform Nicholas Lam ( ). You should note that your data may be used in the production of formal research outputs (e.g. journal articles, conference papers, theses and reports) prior to your withdrawal and so you are advised to contact the research team at the earliest opportunity should you wish to withdraw from the study. On specific request, we will destroy all your identifiable answers, but we will need to use the data collected prior to your withdrawal, and to maintain our records of your consenting participation.

DATA PROTECTION AND CONFIDENTIALITY

Your data will be processed in accordance with the Data Protection Law. All information collected about you (age, gender, email address, training history in orienteering and performance data) will be kept strictly confidential. We will keep the identifiable information about you for one month in order to keep you informed about the results of research and your anonymised data for a minimum of 5 years. Your data will be referred to by a unique participant number rather than by name. The raw data will only be viewed by the lead researcher - Nicholas Lam, and his supervisory team: Dr Shaun Phillips, Professor John Sproule and Dr Tony Turner. All electronic data will be stored on a password-protected computer file. Your consent information will be kept separate from your responses in order to minimise risk.

WHAT WILL HAPPEN WITH THE RESULTS OF THIS STUDY?

The results of this study may be summarised in published articles, reports and presentations. Quotes or key findings will always be made anonymous in any formal outputs unless we have your prior and explicit written permission to attribute them to you by name. Information may also be kept for future research.

WHO CAN I CONTACT?

If you have any further questions about the study, please contact the lead researcher, Nicholas Lam ( ).

If you wish to make a complaint about the study, please contact Dr Shaun Phillips ( ).

In your communication, please provide the study title and detail the nature of your complaint.

For general information about how we use your data go to:

https://www.ed.ac.uk/records-management/privacy-notice-research

Appendix C – Parental information sheet for Study 2 and 3

Appendix C1. Study 2

The parents/ guardians of the participants were advised to read the participant information sheet (Appendix B2.1 or Appendix B2.2) that provided to the participants. No additional parental information sheet was created in Study 2.

THE UNIVERSITY of EDINBURGH

PARTICIPANT INFORMATION SHEET
(For parents / guardians)

Your child is invited to participate in a research study on mental fatigue in orienteering, conducted by Nicholas Lam, a PhD student at the University of Edinburgh. Before deciding whether or not your child should take part, it is important for you and your child to understand the purpose of the research and what it will involve. The study has been approved by the Research Ethics Committee of the University of Edinburgh (Ref: NLAM15042022J23). Please ensure that you take the time to read the following information carefully.

WHAT IS THE PURPOSE OF THE STUDY?

We are looking into whether orienteering athletes experience mental fatigue during orienteering training.

WHY HAVE I BEEN INVITED TO TAKE PART?

Your child has been invited to take part in this study because your child is an orienteering athlete, they have received national level orienteering training and have the ability to fluently read and write in English.

DO I HAVE TO TAKE PART?

Your child’s participation in this research is completely voluntary. If your child does decide to take part, they are free to withdraw at any time and without giving a reason. Deciding not to take part or withdrawing from the study will not affect their rights in any way.

WHAT WILL HAPPEN IF I DECIDE TO TAKE PART?

If your child does decide to take part, please keep this Information Sheet and complete the Informed Consent Form to show that you understand and your child’s right in relation to the research and that you are happy for your child to participate.

Your child will be asked to complete a survey via Qualtrics (an online survey system) on their electronic device (e.g. tablet, laptop, or smartphone) at different time points throughout their training. For instance, if your child is taking part in a 3-day training camp, they will need to submit the survey at the following times:

1. Training day 1 (within 30 mins of waking & within 30 mins after the training)
2. Training day 2 (within 30 mins of waking & within 30 mins after the training)
3. Training day 3 (within 30 mins of waking & within 30 mins after the training)
4. Post-training day 1 (within 30 mins of waking)
5. Post-training day 2 (within 30 mins of waking)

Each survey (part A – D) should take **no more than 5 minutes** to complete. A reminder text messages will be sent via email.

There are four parts in the survey:

Part A

This part will collect your child's age, height, body weight, gender and years of experience in orienteering.

Parts B, C and D

Here, we will ask your child to rate their fatigue, stress, motivation, sleep quality and mood. There are four types of survey scales:

1) Numeric scale, where they select the one number that applies to them:

Version 1:

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

Version 2:

0	1	2	3	4	5	6
○	○	○	○	○	○	○

2) Visual analogue scale, where they slide the bar on the horizontal line:

3) Multiple-choice questions:

Gender

- Male
- Female
- Prefer not to say

4) Open-ended questions:

How many years have you been competing in orienteering?

The research project will take place at **one training camp** over several days**.** Your child can complete the sample survey in their own time at least once as a familiarisation trial before proceeding to the research.

<u>WHAT ARE THE POSSIBLE BENEFITS OF TAKING PART?</u>

There are no immediate benefits to your child's participation in this study. However, doing research like this can enable us to provide your child with some useful information to reduce mental fatigue that might impair their orienteering performance.

Your child's data will be summarised, and they will be informed of the outcomes of the study as part of the debrief. However, quotes or key findings will always be made anonymous.

ARE THERE ANY RISKS ASSOCIATED WITH TAKING PART?

There are no significant risks associated with participation.

WILL MY CHILD'S TAKING PART BE KEPT CONFIDENTIAL?

All the information we collect during the course of the research will be kept confidential and there are strict laws which safeguard your child's privacy at every stage.

WHAT IF I WANT TO WITHDRAW FROM THE STUDY?

Agreeing to participate in this project does not oblige your child to remain in the study nor have any further obligation to this study. If, at any stage, your child no longer wants to be part of the study, please inform Nicholas Lam ( ). You should note that your child's data may be used in the production of formal research outputs (e.g. journal articles, conference papers, theses and reports) prior to your child's withdrawal and so your child is advised to contact the research team at the earliest opportunity should they wish to withdraw from the study. On specific request, we will destroy all your child's identifiable answers, but we will need to use the data collected prior to their withdrawal, and to maintain our records of you and your child's consenting participation.

DATA PROTECTION AND CONFIDENTIALITY

Your child's data will be processed in accordance with the Data Protection Law. All information collected about you and your child (age, gender, email address, training history in orienteering and performance data) will be kept strictly confidential. We will keep the identifiable information about you and your child for one month in order to keep your child informed about the results of research and your child's anonymised data for a minimum of 5 years." Your child's data will be referred to by a unique participant number rather than by name. The raw data will only be viewed by the lead researcher - Nicholas Lam, and his supervisory team: Dr Shaun Phillips, Professor John Sproule and Dr Tony Turner. All electronic data will be stored on a password-protected computer file. Your consent information will be kept separate from your child's responses in order to minimise risk.

WHAT WILL HAPPEN WITH THE RESULTS OF THIS STUDY?

The results of this study may be summarised in published articles, reports and presentations. Quotes or key findings will always be made anonymous in any formal outputs unless we have your child prior and explicit written permission to attribute them to your child by name. Information may also be kept for future research.

WHO CAN I CONTACT?

Appendix C2. Study 3 (Continued)

If you have any further questions about the study, please contact the lead researcher, Nicholas Lam ( ).

If you wish to make a complaint about the study, please contact Dr Shaun Phillips ( ).

In your communication, please provide the study title and detail the nature of your complaint.

For general information about how we use you and your child’s data go to:

https://www.ed.ac.uk/records-management/privacy-notice-research

Appendix D – Participant informed consent form for Study 1 – 3

Appendix D1. Study 1

PARTICIPANT CONSENT FORM

Study Title: The Development of Mental Fatigue in Orienteering: A Delphi Study

Please initial box

1. I confirm that I have read and understood the Participant Information Sheet for the above study.

2. I have been given the opportunity to consider the information provided, ask questions and have had these questions answered to my satisfaction.

3. I understand that my participation is voluntary and that I can ask to withdraw at any time without giving a reason and without my medical care or legal rights being affected.

4. I understand that my anonymised data will be stored for a minimum of 5 years and may be used in future ethically approved research.

5. I agree to take part in this study.

Name of person giving consent	Date	Signature
______________________	___________	____________________________

Name of person taking consent	Date	Signature
______________________	___________	____________________________

Appendix D2.1 Study 2 – Online

Mental Fatigue in Orienteering, Version 3, 30/03/2022

THE UNIVERSITY of EDINBURGH

PARTICIPANT CONSENT FORM

Study Title: Investigation on the development of mental fatigue in orienteering

Researcher's name and contact details:
Nicholas Lam ( )

Please initial box

1. I confirm that I have read and understood the Participant Information Sheet (Version 3 dated 30/03/2022) for the above study.
2. I have been given the opportunity to consider the information provided, ask questions and have had these questions answered to my satisfaction.
3. I understand that my participation is voluntary and that I can ask to withdraw at any time without giving a reason and without my medical care or legal rights being affected.
4. I understand that my anonymised data will be stored for a minimum of 5 years and may be used in future ethically approved research.
5. I agree to take part in the above study and complete the survey for two competition weekends.

Name of person giving consent	Date	Signature
________________________	____________	______________________________
Name of person taking consent	Date	Signature
________________________	____________	______________________________

Appendix D2.1. Study 2 – Online (Continued)

Contact details:

Name: ______________________________

Address: ______________________________

____

____

Contact number: ______________________________

Contact email: ______________________________

Appendix D2.2. Study 2 – Amendment

Mental Fatigue in Orienteering, Version 4, 06/04/2022

THE UNIVERSITY of EDINBURGH

PARTICIPANT CONSENT FORM

Study Title: Investigating on the development of mental fatigue in orienteering

Researcher's name and contact details:
Nicholas Lam (   )

Please initial box

1. I confirm that I have read and understood the Participant Information Sheet (Version 4 dated 06/04/2022) for the above study.

2. I have been given the opportunity to consider the information provided, ask questions and have had these questions answered to my satisfaction.

3. I understand that my participation is voluntary and that I can ask to withdraw at any time without giving a reason and without my medical care or legal rights being affected.

4. I understand that my anonymised data will be stored for a minimum of 5 years and may be used in future ethically approved research.

5. I agree to take part in the above study and complete the survey for two competition weekends.

6. I am aware that participating in this study at the current time may carry risks in relation to potential exposure to COVID-19, and I understand the steps that have been taken in relation to minimising the risks of exposure and transmission.

7. I have not experienced any COVID-19 related symptoms, or been in contact with a known COVID-19 positive individual in the 14 days prior to this research interaction.

Name of person giving consent	Date	Signature
________________________	____________	______________________________

Name of person taking consent	Date	Signature
________________________	____________	______________________________

Contact details:

Name: ____

Address: ____

____

____

Contact number: ____

Contact email: ____

Appendix D3.1. Study 3

Mental Fatigue in Orienteering Training, Version 2, 27/07/2023

THE UNIVERSITY *of* EDINBURGH

PARTICIPANT CONSENT FORM

Study Title: Investigation on the development of mental fatigue in orienteering training

Researcher's name and contact details:
Nicholas Lam ( )

Please tick box

1. I confirm that I have read and understood the Participant Information Sheet (Version 2 dated 27/02/2023) for the above study.
2. I have been given the opportunity to consider the information provided, ask questions and have had these questions answered to my satisfaction.
3. I understand that my participation is voluntary and that I can ask to withdraw at any time without giving a reason and without my medical care or legal rights being affected.
4. I understand that my anonymised data will be stored for a minimum of 5 years and may be used in future ethically approved research.
5. I agree to take part in the above study and complete the survey for one orienteering training camp.

Name of person giving consent	Date	Signature
_______________________	____________	____________________________

Name of person taking consent	Date	Signature
_______________________	____________	_____________________________

Appendix E – Parental informed consent form for Study 2 and 3

Appendix E1.1 Study 2 – Online

Mental Fatigue in Orienteering, Version 3, 30/03/2022

THE UNIVERSITY of EDINBURGH

PARTICIPANT CONSENT FORM

Study Title: Investigation on the development of mental fatigue in orienteering

Researcher's name and contact details:
Nicholas Lam (   )

Please initial box

1. I confirm that I have read and understood the Participant Information Sheet (Version 3 dated 30/03/2022) for the above study.
2. I have been given the opportunity to consider the information provided, ask questions and have had these questions answered to my satisfaction.
3. I understand that the participation of my child is voluntary and that I can ask to withdraw at any time without giving a reason and without my medical care or legal rights being affected.
4. I understand that the anonymised data of my child will be stored for a minimum of 5 years and may be used in future ethically approved research.
5. I consent to my child's participation in this research project for two competition weekends.

Participant name (print): ______________________________

Parent / Guardian name (print): ______________________________

Name of person giving consent	Date	Signature
____________________	__________	________________________

Name of person taking consent	Date	Signature
____________________	__________	________________________

Mental Fatigue in Orienteering, Version 3, 30/03/2022

Contact details:

Name: ____

Address: ____

____

____

Contact number: ____

Contact email: ____

Appendix E1.2. Study 2 – Amendment

Mental Fatigue in Orienteering, Version 4, 06/04/2022

THE UNIVERSITY of EDINBURGH

PARTICIPANT CONSENT FORM

Study Title: Investigation on the development of mental fatigue in orienteering

Researcher's name and contact details:
Nicholas Lam (   )

Please initial box

1. I confirm that I have read and understood the Participant Information Sheet (Version 4 dated 06/04/2022) for the above study.
2. I have been given the opportunity to consider the information provided, ask questions and have had these questions answered to my satisfaction.
3. I understand that the participation of my child is voluntary and that I can ask to withdraw at any time without giving a reason and without my medical care or legal rights being affected.
4. I understand that the anonymised data of my child will be stored for a minimum of 5 years and may be used in future ethically approved research.
5. I consent to my child's participation in this research project for two competition weekends.
6. I am aware that participating in this study at the current time may carry risks in relation to potential exposure to COVID-19, and I understand the steps that have been taken in relation to minimising the risks of exposure and transmission.
7. I have not experienced any COVID-19 related symptoms, or been in contact with a known COVID-19 positive individual in the 14 days prior to this research interaction.

Participant name (print): ________________________________

Parent / Guardian name (print): ________________________________

Name of person giving consent	Date	Signature
____________________	__________	________________________

Name of person taking consent	Date	Signature
____________________	__________	________________________

Contact details:

Name: ______________________________________

Address: ______________________________________

____

____

Contact number: ______________________________________

Contact email: ______________________________________

Appendix E2. Study 3

Mental Fatigue in Orienteering Training, Version 2, 27/02/2023

THE UNIVERSITY *of* EDINBURGH

PARTICIPANT CONSENT FORM

Study Title: Investigation on the development of mental fatigue in orienteering training

Researcher's name and contact details:
Nicholas Lam ( )

Please tick box

1. I confirm that I have read and understood the Participant Information Sheet (Version 2 dated 27/02/2023) for the above study.
2. I have been given the opportunity to consider the information provided, ask questions and have had these questions answered to my satisfaction.
3. I understand that the participation of my child is voluntary and that my child can ask to withdraw at any time without giving a reason and without their medical care or legal rights being affected.
4. I understand that the anonymised data of my child will be stored for a minimum of 5 years and may be used in future ethically approved research.
5. I consent to my child's participation in this research project for one orienteering training camp.

Participant name (print): ____________________________________

Parent / Guardian name (print): ____________________________________

Name of person giving consent	Date	Signature
______________________	___________	____________________________

Name of person taking consent	Date	Signature
______________________	___________	____________________________

Appendix F – Publications

Abstract acceptance letter for BASES Conference 2021

B

EventsAIR <no-reply@eventsairmail.com> on behalf of
BASES 2021 <mail@eventsairmail.com>

Wednesday, 25 August 2021 at 4:21 PM

To: Hui Kwan Nicholas Lam

Poster Presenter Gui...
168.3 KB

Download All • Preview All

You forwarded this message.

Dear Hui Kwan Nicholas,

Thank you again for submitting an abstract for BASES Conference 2021.

Your submission, as detailed further down this email, has been accepted as a Poster presentation.

We are currently finalising the programme and a link to this will be sent early September.

Presenters must register for the conference (including payment of delegate fees) by **23.59 BST on Tuesday 31 August 2021**. Abstracts may be withdrawn from the conference programme if presenters have not registered for the conference by this date. Removed abstracts will not be included in the online supplement of the Journal of Sports Sciences. To register for BASES Conference 2021, please visit www.basesconference.co.uk.

As lead author you will be emailed a PDF of the abstract book in due course for you to proof to ensure that your abstract(s) are how you wish them to be published in the online supplement of the Journal of Sports Sciences.

Please find presenter guidelines attached to help you prepare your presentation. Please ensure you have read these as they include some key information to be aware of and deadlines for sending your content.

Speaker Presentations

Title	International expert consensus on the development of mental fatigue in orienteering: a Delphi study
Paper Number	32
Paper Status	Accepted as Poster
Theme	Sport and Performance
Presenting Author	Hui Kwan Nicholas Lam Affiliations: Human Performance Science Research Group, The University of Edinburgh

Poster Presentation for BASES Conference 2021

International expert consensus on the development of mental fatigue in orienteering: a Delphi study

Hui Kwan Nicholas, Lam[1], John, Sproule[1], Tony, Turner[1], Paul, Murgatroyd[2], Graham, Gristwood[2], Hugh Richards[1], Shaun, Phillips[1]
[1] Human Performance Science Research Group, The University of Edinburgh; and [2] British Orienteering, United Kingdom

THE UNIVERSITY of EDINBURGH

Background

Orienteering is a sport that constantly challenges individuals to formulate a route to the checkpoint using a map and compass to travel in unfamiliar terrain as quickly as possible [1]. Importantly, the overall exercise intensity is largely dependent on the tactics and the route identified by the orienteers [1]. However, no research has investigated mental fatigue in orienteering nor standardising the definition of mental fatigue (MF) in sport. The aim of this study was to seek international orienteering expert consensus on the following issues that could be used to recognise and address MF in orienteering: (1) the definition of MF, (2) the development of MF, (3) the cause of MF, (4) the influence of MF, and (5) the methods to reduce MF.

Methods

1. Following ethics approval, a **three-round** Delphi survey was conducted online through Jisc Online Surveys

2. Eligibility criteria of the expert panel:
(1) ≥ 10 years experience in coaching or competing in orienteering
(2) Represented once at national level
(3) Read and write in English Fluently
(4) ≥ 18 years old

3. 24 experts from 10 different countries participated:
7 coaches: 16.7 ± 7.16 years of experience
17 athletes and former athletes: 16.2 ± 7.27 years of experience

4. The questions in round 1 survey was developed based on literature while round 2 and 3 were developed using the consensus and qualitative feedback from the experts.

5. For each survey round, experts were given 2 weeks to respond and separated by 4-6 weeks for data analysis [2]. The threshold of consensus in this study was ≥ 70% [3].

Conclusions and Recommendations

Orienteering experts revised the definition of MF and identified the key components regarding the development of MF in orienteering. These findings could be useful in improving the ecological validity of the MF protocol. Experts also highlighted that MF could develop either acutely or chronically, which provide a new direction for future experimental research to investigate MF.

Results

≥ 70%
Agreed the following components

Survey	Response rate (percentage of responses)
Round 1	24/25 (96%)
Round 2	19/24 (79%)
Round 3	18/19 (94%)

Definition

Mental fatigue is charcterized by the inability to maintain concentration and process information for decision-making efficiently and effectively after a prolonged period of cognitively load activity.

Development

In orienteering training:
- Insufficient recovery
- Complexity of the task
- Demand of technical training
- Non-orienteering challenges (e.g from work or school)

In orienteering competition:
- Mental condition
- Physical condition
- Prolonged racing schedule or season
- Insufficient mental rest during competition

Causes

In orienteering training:
- Route choice selection
- Map reading (including map visualization)
- Navigation (react to surround environment/ features, terrain)

In orienteering competition:
- External pressures/ stress
- Complexity (difficult of the task)
- Concentration level (amount of focus required for the task)

Influences

Negative psychological changes:
- Distraction
- Demotivated
- Confusion (e.g. mixed up, uncertain)
- Fatigue (e.g. worn out, exhausted, sleepy, tired)

- Reaction time
- Rating of perceived exertion
- Subjective rating of tiredness
- Accuracy of decision-making

Solutions

- Mental breaks
- Supplementation

Training that could effectively reduce MF:
- Mental training
- Orienteering technical training only
- Combined physical and orienteering technical training
- Repeated high intensity and/ or high-quality orienteering technical training

References

1. Batista, M. M., Paludo, A. C., Gula, J. N., Pauli, P. H., & Tartaruga, M. P. (2020). Physiological and cognitive demands of orienteering: a systematic. *Sport Sciences for Health*. doi:10.1007/s11332-020-00650-6
2. Hsu, C.-C., & Sandford, B. A. (2007). The Delphi technique: Making sense of consensus. *Practical assessment, research & evaluation, 12*(10), 1-8.
3. McCall, A., Pruna, R., Van der Horst, N., Dupont, G., Buchheit, M., Coutts, A. J., ... & Fanchini, M. (2020). Exercise-Based Strategies to Prevent Muscle Injury in Male Elite Footballers: An Expert-Led Delphi Survey of 21 Practitioners Belonging to 18 Teams from the Big-5 European Leagues. *Sports Medicine*, *50*(9), 1667-1681.

Published abstract at BASES 2021 Conference

D3.S3 International expert consensus on the development of mental fatigue in orienteering: a Delphi study

Hui Kwan Nicholas Lam[1], John Sproule[1], Tony Turner[1], Paul Murgatroyd[2], Graham Gristwood[2], Hugh Richards[1], Shaun Phillips[1]

[1]Human Performance Science Research Group, The University of Edinburgh, Edinburgh, United Kingdom, [2]British Orienteering, United Kingdom

Orienteering is an outdoor sport that requires individuals to navigate and identify the optimal route, in a natural environment, using a compass and map. Mental fatigue (MF) is a performance constraint in both psychological and physiological aspects, affecting orienteers' navigational and visuospatial performance. However, the development of MF is inadequately uniform to develop a clear guideline in addressing MF in orienteering. Therefore, the aim of this research was to seek international orienteering expert consensus regarding the definition, development, cause, influence of and recovery from MF in orienteering based on their practical experience. Following ethics approval, a three-round Delphi survey was conducted online with twenty-four orienteering coaches, athletes and former athletes from 10 different countries with international orienteering competition experience (16.7 ± 7.16 and 16.2 ± 7.27 years respectively). The threshold of consensus in this study was ≥ 70% agreement among respondents. The experts agreed that MF exists in daily life, orienteering training and competition with a substantial negative effect on orienteers conscious decision-making performance and psychological responses. There was an explicit agreement that the form of MF that athletes experienced differs in orienteering training and competition. However, there was no agreement that MF would impact endurance and high-speed running performance during orienteering. The experts also disagree that the extent of MF that orienteers experience is based on the duration of the task. This study highlights issues specific to the development of MF in orienteering for future investigations, and provides consensus-based recommendations for orienteering athletes and coaches to minimise the influence of MF on sports performance.

D3.S3 An insight into short-sprint coaches' knowledge and use of periodisation models and training methods - Evidence from the Sri Lankan context

Jeganenthiran Sellathurai[1,2,3], Nick Draper[1]

[1]University of Canterbury, New Zealand, [2]Sabaragamuwa University of Sri Lanka, Sri Lanka, [3]Sri Lanka Track and Field Coaches Association, Sri Lanka

Recent developments in applied sports coaching that use periodized training strategies to improve athletic performance have become increasingly attractive to coaches, athletes, and strength and conditioning practitioners. Coaches' knowledge and skills are crucial to the successful application of periodisation and training methods for improving performance. Despite its popularity and importance, little is known about the Sri Lankan context. As a result, this formative exploratory study aimed to examine the knowledge of, and application of, periodisation and training methods used by Sri Lankan elite-level coaches working with short-sprint athletes to achieve desired goals. Ten (n=10) expert short-sprint coaches volunteered to participate in the study, with data collected via semi-structured interviews. The data were analysed inductively, involving 'discovering patterns', 'themes' and 'categories' using the NVivo 12 qualitative software. The techniques and procedures of Brawn and Clark were also followed (Braun, V. & Clarke, V, 2006, Qualitative research in psychology, 3(2), 77-101). Four primary themes emerged from the interview data. These included "Periodisation models", "Monitoring training", "Strength development", and "Speed development". Results revealed that while coaches reported minimal or inadequate knowledge on periodised training, there appears to be a gap between coach knowledge of periodised training, strength and speed training load, and practice such as monitoring training load. They believed that their knowledge was inadequate to transfer athletes to the Olympics. The findings also highlight the importance of providing adequate coach education and development to enable coaches better prepare their athletes in Sri Lanka.

D3.S3 Quantifying methods of body mass losses of United Kingdom powerlifters in competition preparation

Laura Wilson[1], Tara Wood[1], Christopher Curtis[1]

[1]Middlesex University, London, United Kingdom

Previous research in Powerlifting (PL) has qualitatively investigated rapid weight-loss (RWL) in PL athletes and body image (Nolan et al. 2020, Journal of Strength and Conditioning Research) however limited research exists in quantifying such methods adopted in PL. This study aimed to quantify methods of body mass losses during competition preparation of male and female PL athletes in the United Kingdom. Following institutional ethical approval a total of n=37 (n=19 female, n=18 male) competitive powerlifters completed an anonymous online questionnaire assessing RWL methods. Normality was assessed via Shapiro-Wilks test. A series of one-way analysis of variance (ANOVA) tests were used to identify any significant differences between dependent variables (participant PL category and biological sex) against independent variables (undertaking RWL, timeframe and advice sought). Following this, multiple regression analysis was carried out to determine the contribution of biological sex and PL category as factors relating to the adoption of RWL, timeframe of weight control and advice sought. The alpha level for significance was set at $p \leq 0.05$. Commonly reported methods of weight loss were gradual dieting (49%), fluid restriction (46%), and water loading (51%). Differences between PL category (Junior, Open, Masters One) and adopting RWL was observed ($F(1,35) = 4.506$, $P \leq 0.05$). PL category is a predictor of undertaking RWL ($R^2adj = 0.160$, $F(2, 34) = 4.429$, $P \leq 0.05$), whilst biological sex is a predictor of timeframe of undertaking RWL ($R^2adj = 0.123$, $F(2, 34) = 3.534$, $P \leq 0.05$). RWL strategies are adopted by PL athletes in order to

Abstract acceptance letter for International Congress on Solders' Physical Performance 2023

ICSPP 2023 Submission Decision

A ArmyPers-ICSPP2023@mod.gov.uk <ArmyPers-ICSPP2023@mod.gov.uk>
To: Nicholas Lam

Wednesday, 3 May 2023 at 5:36 PM

Dear **Hui Kwan Nicholas Lam**

Thank you for your submission to ICSPP 2023. We are pleased to inform you that your submission '**The Potential Effects of Mental Fatigue on Marksmanship Judgment Performance: Insights from Research on Physically and Cognitively Demanding Sport**' has been accepted for **a poster presentation** at ICSPP 2023.

If you have received multiple emails, please read each one carefully, as each email contains a different letter for each submission.

Revisions
Reviewers may have requested some revisions to your submission. The Scientific Committee will be in contact in due course to request any revisions and to finalise your submission for the conference.

Scheduling
The details of your presentation date and time will be sent in due course.

Presentation Guidelines
Presentation guidelines will be sent in due course, and these will also be made available on the ICSPP webpage.

Withdrawing
In the event you can no longer present, please immediately inform the Scientific Committee at ArmyPers-ICSPP2023@mod.gov.uk.

Registration
All presenters are required to register and pay the registration fee by Friday 30th June 2023. This is a change to the date on the ICSPP website. Please note that places, including early bird registration, are on a strictly first come first served basis, so we encourage presenters to register as soon as possible once the link goes live. Presenters not registered by 30th June may have

Understanding the impact of mental fatigue: Competitive orienteering as a model for mental fatigue studies in military personnel

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Purpose

- Mentally fatigued soldiers make significantly more marksmanship decision errors [1].
- Mental fatigue (MF) negatively impacts reaction time, endurance, and decision-making performance in sports [2].
- MF can naturally develop during training camps [3].
- Orienteering involves running through unfamiliar terrain, utilizing a map and compass to reach checkpoint within a time limit
- Orienteers, who shared some similar fundamental skills with soldiers, were chosen as a model to explore the potential effects of MF.
- The study aimed to assess the impact of MF on orienteers during training camp

Methods

Ten national junior orienteers participated (Age: 15-17 years, height: 1.69 ± 0.1m, body mass: 59.9 ± 5.3)

4-day competition preparation camp

Day 1	Sprint & Middle-distance
Day 2	Long-distance
Day 3	Relay & night orienteering
Day 4	Relay

Measurements taken:
- Within 30 mins of waking (PRE1-4)
- Immediately after training (POST1-4)
- Within 30 mins of waking on 24- and 48-hours after training camp (24POST & 48POST)

Measured variables:
0-100 Visual Analogue Scale (VAS)
Mental Fatigue, Physical Fatigue (PF), Tiredness & Stress

Data Analysis:
- Exploratory Software for Confidence Intervals.
- Cohen's *d* to indicate the magnitude of changes.

Results

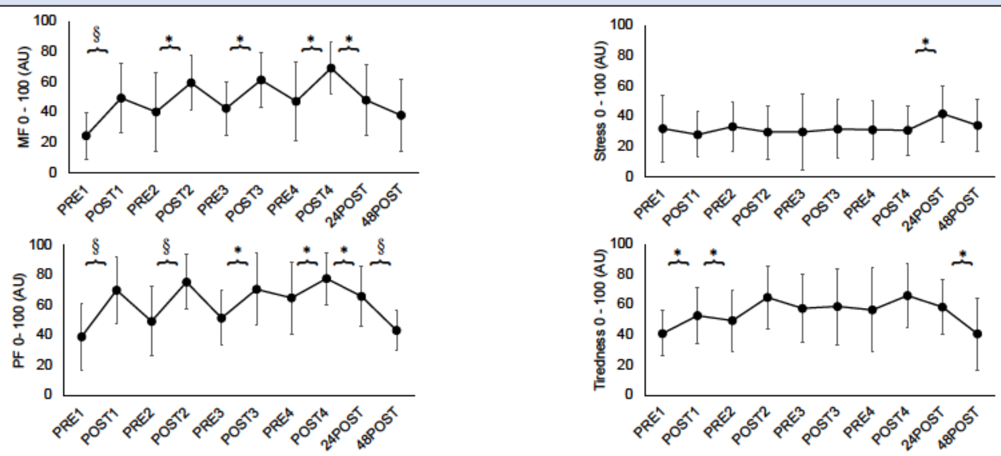

Figure 1. The changes in psychological responses during and after the training camp. The black line represent the mean value.
*: moderate change compared to PRE condition ($d \geq 0.6$); §: large change compared to PRE condition ($d \geq 1.2$).

Conclusion

- Ratings of MF progressively increased during a 4-day training camp.
- Changes in MF were distinct from other fatigue-related variables, suggesting MF represents a distinct fatigue construct.
- Ratings of MF and PF remained above baseline 48 hours after the camp, indicating a potentially prolonged impact on psychophysiological responses.
- The data suggests a potential need to establish an effective MF management strategy during training camps.

Military Impact

- Extended military training may impact soldiers' level of MF.
- Previous research shows that acute MF can impair marksmanship judgment [1], endurance and reaction time [2], suggesting its accumulation might also affect overall physical readiness.
- Perceived MF and other fatigue-related variables warrant separate investigations in future military research.

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Board 38: Understanding the impact of mental fatigue: competitive orienteering as a model for mental fatigue studies in military personnel

Hui Kwan Nicholas Lam [1], John Sproule [1], Anthony P Turner [1], Shaun M Phillips [1]

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Purpose: The presence of mental fatigue (MF) has been demonstrated to have a detrimental effect on a variety of cognitive tasks associated with human performance in the military. Previous research also indicated that MF can impair reaction time, endurance, and decision-making performance in sport. Orienteering involves running through an unknown terrain whilst using a map and compass to reach the next checkpoint within a specified time limit, requiring athletes to endure both physical and cognitive fatigue. As some fundamental skills of soldiers and orienteers are similar, orienteers were chosen as a model to determine if those regularly exposed to a high physical and cognitive load environment are affected by MF. The aim of this study was to assess whether MF affects orienteers during training camps. **Methods:** Ten

national junior orienteers participated in the study (age: 15 to 17 y, height: 1.69 ± 0.10 m, body mass: 59.9 ± 5.3 kg). They completed a 4-day simulated orienteering race which incorporated sprint, middle-distance, long-distance, relay, and night orienteering. Ratings of perceived MF and physical fatigue (PF) were measured with a 0 to 100 visual analogue scale. Measurements were taken within 30 minutes of waking, immediately after each training session, and one and two days after the completion of the training camp. Data was analysed using the mean difference and magnitude of changes. Data were presented as effect size [95%CI]. **Results:** There was a moderate to very large change in MF before and after each training session (Day 1: d = 1.29 [0.16 , 2.37]; Day 2: d = 0.85 [0.03, 1.64]; Day 3: d = 1.06 [0.26, 1.83]; Day 4: d = 1.00 [0.35, 1.62]) with 48 h post presenting a moderate increase from the pre-training value (d = 0.67 [−0.22 , 1.54]). A similar trend was observed in PF but with a trivial to moderate difference between PF and MF. **Conclusions:** This research concludes that both MF and PF increased and accumulated during a 4-day training camp and did not return to pre-training levels 48 hours after the camp. This research demonstrates that even those who are physically and mentally trained can still experience MF from training. **Military Impact:** It is feasible that military personnel may suffer from MF due to their training, and the inability to recover swiftly from the increased MF could potentially lead to a further decline in their judgement accuracy following a long period of training if there are no suitable strategies in place to manage the MF.

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SPORT AND EXERCISE PSYCHOLOGY

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International orienteering experts' consensus on the definition, development, cause, impact and methods to reduce mental fatigue in orienteering: A Delphi study

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ABSTRACT

Orienteering is an outdoor activity wherein participants use a map and compass to locate control points and choose the quickest path to the next control point in a natural environment. Attentional focus, rapid decision-making, and high aerobic fitness may influence orienteering performance. Therefore, this research aimed to seek international orienteering expert consensus regarding the definition, development, causes, influences and methods to reduce mental fatigue (MF) in orienteering based on practical experience. Following ethical approval, a three-round Delphi survey was conducted online with twenty-four orienteering coaches and athletes (or former athletes) from 10 different countries with international orienteering competition experience. The threshold of consensus was ≥ 70% agreement among respondents. The experts agreed that MF exists in daily life and orienteering with a substantial negative effect on their conscious decision-making performance and psychological responses. The experts disagreed that the form of MF that athletes experienced in orienteering training are similar to the competition. However, there was no agreement that MF would impact endurance and high-speed running performance during orienteering. This research refines the definition of MF and summarises the distinctions in what causes MF in orienteering training and competition, implying that MF should be addressed separately.

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SPORT AND EXERCISE PSYCHOLOGY

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The impact of sprint, middle-distance, and long-distance orienteering races on perceived mental fatigue in national level orienteers

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ABSTRACT

Experiencing mental fatigue (MF) before an orienteering race can lead to a slower completion time. This study aimed to explore the changes in perceived MF, mood and other psychological responses during an orienteering competition. Sixteen national level orienteering athletes (20.8 ± 4.9 years) provided informed consent and completed the online surveys, before and immediately after each race, and 24- and 48-hours post competition (48POST). This study measured MF, physical fatigue, stress, tiredness and motivation using 0–100 Visual Analogue Scale, and the mood was assessed using The Brunel Mood Scale (BRUMS). A moderate to large increase in MF (ES = 0.93 [0.54 to 1.31]), BRUMS fatigue (ES = 0.61 [0.3 to 0.92]), and PF (ES = 1.21 [0.81 to 1.61]) was reported following orienteering races. A small increase in tiredness and BRUMS confusion, and a small decrease in motivation, stress and BRUMS vigour was also reported. There was a delay in recovering from the MF elicited by competition, with a small increase in MF (ES = 0.54 [0.08 to 1.15]) at 48POST compared to the pre-competition value. This study found that orienteers experience MF during competition and have a delayed recovery that can last up to two days after the competition.

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KEYWORDS
Cognitive fatigue; delayed recovery; mental exertion; well-being

Introduction

Mental fatigue (MF) has been defined as a negative psychobiological state that happens during a prolonged period of cognitively demanding task and results in an increased subjective tiredness and reduced endurance performance (Habay et al., 2021; Lam et al., 2021; Van Cutsem et al., 2017). Perceptions of MF may vary between individuals and sports (Lam et al., 2023; Russell et al., 2019). Consequently, this study adopted the revised definition from international orienteering experts which defined MF (Lam et al., 2023) – an inability to maintain concentration and process information for decision-making efficiently and effectively after a prolonged period of cognitively loaded activity. According to Martin et al. (2018), an increase in mental exertion can impair brain executive functions, resulting in impaired decision-making and self-regulation. This impairment subsequently contributes to poor endurance performance.

In contrast to the conclusion of previous systematic reviews and meta-analyses (Giboin & Wolff, 2019; Habay et al., 2021; Van Cutsem et al., 2017), a recent Delphi study with international orienteering experts agreed that MF exists in orienteering training and competition but disagreed that it has a negative impact on orienteer's speed or endurance running performance (Lam et al., 2023). The discrepancy between the views of orienteering experts and the literature may be attributed to the potential differences in the perception and interpretation of MF between practitioners/athletes and researchers, as reported in Russell et al. (2019). Previous studies have shown that MF induced via a computerized cognitively demanding task, such as the Stroop-colour task, can impair decision-making, reaction time and accuracy in open skill sports (Habay et al., 2021; Sun et al., 2021), and reduce efficiency in using environmental information during soccer small-sided games, thereby affecting the execution of tactical plans (Coutinho et al., 2018). Although Batista et al. (2021) observed that orienteers had a slower completion in a subsequent 3.1 km simulated orienteering race after performing a computerized cognitively demanding task for 30 mins, it has the same limitation as most of the investigations on MF, in which the MF induced was far from the reality of the sport. The fundamental nature of orienteering requires orienteers to gather as much information from the surrounding environment as possible in order to identify the most energy-cost-efficient and quickest route to each control point using a map and compass (Batista et al., 2020; Creagh & Reilly, 1997). It has been observed that mentally fatigued individuals may experience impairments in their visual search behaviour, resulting in a delay in responding to dynamic situations (Zeuwts et al., 2021). This suggests that mentally fatigued orienteers may have difficulties in effectively gathering environmental information, leading to slower completion times. This support previous findings with soccer players, who presented more conscious decision-making errors and poorer technical plan execution in a mentally fatigued state (Coutinho et al., 2017; Sun et al., 2021, 2022).

A recent systematic review found that the level of physical fitness level of individuals does not have an influence on susceptibility to MF (Habay et al., 2023). However, there is evidence indicating that well-trained athletes and

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ORIGINAL PAPER

EJSS Official ECSS Journal Open Access WILEY

Changes in perceived mental fatigue, physical fatigue and mood state during a 4-day national junior orienteering competition preparation camp

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Abstract

Mental fatigue (MF) has been shown to acutely impair the psychological responses and endurance running performance of orienteers. This study aimed to explore MF levels experienced by orienteers during a 4-day competition preparation camp that consisted of simulated sprint, middle-distance, long-distance, relay and night races. Eleven national junior orienteers participated in the study (age: 15–17 years, height: 1.69 ± 0.07 m and body mass: 59.9 ± 5.22 kg). Subjective ratings of MF, motivation, stress, physical fatigue (PF) and tiredness were measured using a 100-mm visual analogue scale. The Brunel Mood Scale (BRUMS) was utilized to assess the mood state of the orienteers. The self-report measures were taken within 30 min of waking, immediately after the post-training session, and after 24 and 48 h following the final training session. The pre–post orienteering training combined analysis showed that there was a moderate increase in perceived MF (ES = 1.06 [0.66, 1.45]), PF (ES = 1.07 [0.69, 1.45]) and BRUMS fatigue (ES = 0.74 [0.4, 1.1]) after orienteering training. At 48 h post the final training session, MF remained moderately elevated (ES = 0.86 [−0.07, 1.75]), while PF also remained elevated to a small extent (ES = 0.46 [−0.46, 1.39]) compared to the pre-training values. A moderate impairment was still observed in BRUMS vigor (ES = −1.02 [−1.65, −0.36]), but BRUMS confusion scores were moderately lower (ES = −0.85 [−1.71, 0.04]) than pre-training values. This study found that orienteering training induced acute MF, persisting for at least 48 h after the final session.

KEYWORDS
athlete wellbeing, cognitive fatigue, cross-country, mental exertion, perception

Highlights

- National junior orienteers experienced perceived mental fatigue during an orienteering training camp, and recovery of psychological responses was incomplete after 48 h.

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Human Kinetics
INVITED COMMENTARY

Future Directions in Understanding Acute and Chronic Effects of Mental Fatigue in Sports: A Commentary on Bridging Laboratory Findings and Real-World Applications

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Background: Mental fatigue (MF) is a psychobiological state that could negatively impact physical and cognitive performance, although the extent of this impact remains controversial. While laboratory studies have provided valuable insights into the acute effects of MF, their ecological validity in real-world sport settings remains limited. Recent research indicates that MF can naturally arise during sport activities, leading to chronic effects on endurance and perceptual-cognitive skills. These effects may persist beyond individual sessions, potentially increasing the risk of injury due to their cumulative nature. ***Purpose:*** This commentary aims to guide future research by emphasizing the need to investigate the natural occurrence and chronic effects of MF in applied sport settings. ***Conclusions:*** Understanding how MF develops and manifests in real-world settings, particularly individual differences in perception and response, is crucial for creating more effective management strategies. Addressing these factors will enable better support for athletes who may experience prolonged periods of MF that could affect their training and competitive performance. Future research should prioritize studying MF in natural sport settings to enhance the ecological validity of findings. By focusing on the chronic and cumulative nature of MF, as well as individual variability, researchers can develop more tailored and effective strategies for managing MF. This research will not only bridge the gap between laboratory studies and real-world applications but also contribute to more precise monitoring and intervention techniques. Ultimately, these advancements will improve athletes' ability to maintain peak performance and reduce the risk of injury, thereby enhancing overall athletic well-being.

Keywords: daily monitoring, cognitive fatigue

Mental fatigue (MF) is a psychobiological state resulting from prolonged engagement in high cognitively demanding tasks, which could negatively impact physical performance.[1] It is crucial to understand that MF is a subjective psychological state, with individual perceptions and interpretations varying significantly, as noted by Russell et al.[2] This subjectivity highlights the need for a more context-specific definition and a deeper understanding of the effects of MF to increase the specificity of discussions. The impact of MF in sport was traditionally investigated by requiring participants to perform prolonged, nonsport-specific, computerized cognitive tasks, such as the Stroop color task, to induce MF.[1] A recent editorial article has highlighted that increasing internal validity in laboratory-based MF investigations has enhanced our understanding of the potential effects of MF on sports performance, with evidence suggesting that both sport- and nonsport-related activities can influence MF states.[3] However, the practicality of these findings remains limited due to challenges in monitoring and the varied impact across different sports, which cannot be fully identified through laboratory-based investigations. This indicates a need for further research into the specificity and practicality of MF to provide a more comprehensive understanding. A Delphi study involving elite orienteering practitioners and athletes found no consensus regarding the impact of MF on endurance performance, suggesting that the current definition of MF may require refinement.[4]

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This also suggests that investigation might benefit from shifting its focus toward cognitive performance rather than primarily on endurance capacity.[4] Additionally, a major limitation of the existing evidence is the failure to address the participant's prior knowledge of MF,[5] leading to unstandardized interpretations and understanding during experiments. This inconsistency raises concerns regarding the reliability of MF assessments, as it remains unclear whether participants rated their MF consistently, thereby introducing potential confounding variables. Importantly, previous research on meta-cognition reveals that understanding psychological state is closely linked to self-awareness, requiring individuals to monitor and adjust their cognitive strategies during tasks.[6] Therefore, without a clear understanding of MF in sports, it becomes challenging for both researchers and athletes to identify and define this phenomenon effectively. Future research should prioritize the development of a more standardized methodology for assessing MF, ensuring that participants have a clear and consistent understanding of the concept of MF. To address this, previous research has explored how elite athletes and practitioners perceive MF in sport to better understand variations in susceptibility to MF,[2,4] as interindividual differences in MF susceptibility have been reported.[5,7] A novel approach was adopted in 2 recent observational studies with elite orienteers,[8,9] where participants were provided with a definition of MF, refined by orienteering experts,[4] to standardize their understanding when rating MF scales. This approach ensures that participants in these studies share a consistent foundation and interpretation of MF in orienteering, potentially enhancing the comparability of MF ratings across individuals due to this shared understanding. It is notable that most investigations