Saarland University, Institute of Sports and Preventive Medicine

University of Technology Sydney

MENTAL FATIGUE IN FOOTBALL

By

Chris Thompson

This thesis is presented for the award of a Doctor of Philosophy (Sports Medicine) from the Medical Faculty, Saarland University, Saarbrücken, Germany, and University of Technology Sydney (UTS), Australia.

Declaration

I, Christopher James Thompson, declare that this thesis, is submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy in the Institute of Sport and Preventive Medicine, Saarland University (Germany) and at the University of Technology Sydney (Australia) in the Sport and Exercise Discipline Group, Faculty of Health, conducted jointly under the Memorandum of understanding between both institutions as part of an international joint PhD program.

This thesis is wholly my own work as the sole author unless otherwise referenced or acknowledged. As such, I also certify to the best of my knowledge and belief that this thesis does not:

i. incorporates any material previously submitted for a degree or diploma in any institution of higher education without acknowledgement;

ii. contain any material previously published or written by another person; where due reference is made in the text; or

iii. contain any defamatory material

I also acknowledge that this research was supported by Saarland University.

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree at any other academic institution except as fully acknowledged within the text. This thesis is the result of a Collaborative Doctoral Research Degree program with Saarland University and the University of Technology Sydney.

I also grant permission for the libraries at Saarland University and University of Technology Sydney to produce duplicate copies of my thesis as required.

Chris Thompson   Date: 24/05/2020

ACKNOWLEDGEMENTS

Firstly, I wish to thank my supervisors for their guidance and support over the past three years. Prof Tim Meyer and Dr Sabrina Skorski, thank you for your open-mindedness throughout the project and putting me at ease through some of the difficult times (plus dealing with my unique personality!). Moving to Germany and learning a new language and culture was the greatest experience of my life, and it wouldn't have been possible without you both. A special mention goes to Dr Job Fransen, the most selfless and helpful person I have ever met. Thank you for all the hours you spent making me a better academic and giving me a more positive outlook on life. Last but not least, thank you Prof Aaron Coutts for everything you have done. You have been a supervisor, friend and part-time therapist! You stuck your neck out and got me through some very hard times, something I will never forget.

A special mention must also go to several mentors I have been fortunate to collaborate with throughout the PhD. Thank you to Dr Mark Noon, Dr Paul Balsom, Dr Steve Barrett and Dr Naomi Datson. Your time and input allowed my work to be as relevant to elite football as it could possibly be. I also owe a lot to Dr Chris Towlson, Dr Mitch Smith, Dr Liam Harper and Dr Andy Smith. Your support and devil's advocate challenged me to become a better academic and learn new skills. I also wish to thank Curt Taylor for making a lot of this thesis come to reality. Without your time dedicated to helping me recruit participants, I'm not sure where I would be!

Since completing the final parts of the thesis alone, I have further appreciated the value of friends. To my fellow PhD Buros, I thank you for making the last three years indescribably hilarious and crazy. Bob, you're the most intelligent person I have met, and I miss bonding over our similarly shocking taste in music and British humour. Ross, you brought out the best and worst in me, and I couldn't be more grateful. We were the Yorke and Cole of SB and I take away some fantastic memories. Adam, you are the brother I never had. Ida, your positivity was infectious, and you (sometimes) kept me on the straight and narrow. Hugh, you're a natural born charmer who knows how to work a room, and you always filled me with self-belief and positive vibes. You made it acceptable to dab as well! Denny, your laugh alone made me laugh, and I will always be ten minutes behind transfer rumours in your absence. Schulze, I miss your office DJ antics, plus I cannot look at Tony Yeboah the same way now. Mat, you're the king of the one-liners and one of the nicest people I have ever met. Ludwig, you are Ludwig – please never change!

Finally, without my family, I would not be in this position. Dad, thank you for making me a laid back individual. This made the PhD process a lot less stressful (and probably passed the stress on to some other unfortunate soul!). Mum, you always instilled into me that it doesn't matter what anyone else thinks of you, and that you should go your own way. We had our hard times when I was growing up and it made me a more caring and resilient person. To my sister Laura, you drove me mad as a child correcting me on my grammar and spelling, but without having you as a role model growing up, there's no way I would have gone to university. I still believe we are adopted, and one day we'll go and find our real parents! Finally, and most importantly, my late grandparents John Joseph Thompson and Mary Monica Thompson. You believed in me as a child and gave me the confidence to go and succeed. I am only sorry you are not here to see me do the things I told you I would. I like to think you are somewhere looking over me and proud of my achievements. There's not an hour that goes by when I am not thinking of you both, and your memory got me through the difficult times.

The format of this thesis is aligned with the 'Thesis by Publication' format as per the standards of both Saarland University and the University of Technology Sydney.

LIST OF PUBLICATIONS RELEVANT TO THE THESIS

Published:

Smith, M. R., Thompson, C., Marcora, S. M., Skorski, S., Meyer, T., & Coutts, A. J. (2018). Mental fatigue and soccer: current knowledge and future directions. *Sports Medicine*, *48*(7), 1525-1532.

Thompson, C. J., Fransen, J., Skorski, S., Smith, M. R., Meyer, T., Barrett, S., & Coutts, A. J. (2018). Mental fatigue in football: Is it time to shift the goalposts? An evaluation of the current methodology. *Sports Medicine*, *49*(2), 177-183.

Thompson, C. J., Noon, M., Towlson, C., Perry, J., Coutts, A. J., Harper, L. D., Skorski, S., Smith, M. R., Barrett, S., Meyer, T. Understanding the presence of mental fatigue in English academy soccer players. Journal of Sports Sciences, 1-7.

Thompson, C., Fransen, J., Beavan, A., Skorski, S., Coutts, A., & Meyer, T. (2020). Understanding the influence of a cognitively demanding task on motor response times and subjective mental fatigue/boredom. *Brazilian Journal of Motor Behavior*, *14*(01), 33-45.

Under review:

Understanding the cognitive demands experienced by professional soccer players: A perspective of English Football League and National League players. Chris J Thompson, Chris Towlson, John Perry, Aaron J Coutts, Mark Noon, Liam D Harper, Sabrina Skorski, Mitchell R Smith, Steve Barrett & Tim Meyer. Journal of Sports Sciences (under review).

Understanding the presence of mental fatigue in elite female football. Chris J Thompson, Andy Smith, Aaron J Coutts, Sabrina Skorski, Naomi Datson, Mitchell R Smith & Tim Meyer. Qualitative Research in Sport, Exercise and Health (under review).

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

ACC – Anterior cingulate cortex

AX-CPT – AX Continuous Performance Task

BET – Brain endurance training

BRUMS – Brunel Mood Scale

CCA – Continuous cognitive activity

dRPE – differential Rating of Perceived Exertion -

DL-PFC – Dorsolateral prefrontal cortex

ECG – Electrocardiogram

EEG – Electroencephalography

ERN – Error-related negativity

ERP – Event-related potential

fNIRS – Functional near-infrared spectroscopy

HIA – High intensity activity

HRV – Heart rate variability

LC-NE – Locus-coeruleus norepinephrine

LIA – Low intensity activity

LSPT – Loughborough soccer passing test

LSST – Loughborough Soccer Shooting Test

MVC – Maximal voluntary contraction

NE – Norepinephrine

POMS – Profile of Mood State

RPE – Rating of Perceived Exertion

SART – Sustained attention to response task

SNR – Signal-to-noise ratios

VAS – Visual analogue scale

Yo-Yo IR1 – Yo-Yo intermittent recovery level 1

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

INTRODUCTION: Mental fatigue is a psychobiological state experienced following exposure to cognitively demanding tasks. Anecdotal evidence shows that mental fatigue can impair football (soccer) performance based on the cognitive demands of match play, fixture congestion, receiving high volumes of tactical information and internal and external pressures to succeed. In six original investigations, induced mental fatigue has negatively influenced football specific skill, physical, tactical and decision-making performance. However, these studies share consistent limitations, which include the use of cognitive tasks with low ecological validity to induce mental fatigue, as well as the recruitment of sub-elite or recreational players. Further research is required to address the limitations of the current research, investigate the relevance of current methods employed to induce mental fatigue, and to understand the true cognitive demands experienced by elite level football players. Therefore the aims of this thesis were as follows: i) to evaluate the applicability of the current mental fatigue research to elite football settings, ii) understand the relevance of the modified Stroop task in inducing mental fatigue, plus its impact on using implicit and explicit information, and iii) use a mixed methods approach to elucidate cognitive demands and influence on performance in elite male, female and academy football players.

METHODS: i) A literature review was conducted to understand the collective impact of induced mental fatigue on football specific performance. ii) A current opinion article critically examined the methodology of the current mental fatigue in football research, with recommendations provided for future study designs. iii) The modified Stroop task was assessed for its impact on using implicit and explicit cues, plus boredom, a construct similar to the demands of mental fatigue. In addition, the impact of a brief rest period from cognitively demanding activity was measured. iv) English Football League and National League players completed an online survey which investigated the impact of football and lifestyle specific cognitive activities on perceived mental fatigue and impact on performance. v) An additional survey was completed by elite English academy football players (U14 – U23) which explored the effects of football and adolescent specific activities on perceived mental fatigue and impact on performance. vi) Focus group interviews explored the psychological demands of elite female football.

RESULTS: i) Mental fatigue studies have used repetitive cognitive tasks with low contextual interference which do not resemble the real-life cognitive demands (i.e. high contextual interference in a dynamic environment) of elite football. ii) The modified Stroop elicits high subjective mental fatigue and boredom ratings which significantly reduce (but not to baseline levels) following a short break. iii) In elite English Football League/National League and academy football, any cognitive tasks completed are short and frequent (intake of tactical information, media commitments, travel) with a negligible influence on perceptions of mental fatigue and performance. A contrast was evident in elite female football, where travel, intake of excessive tactical information and internal pressure to succeed were commonly cited as psychological demands.

DISCUSSION: Mental fatigue may be a transient sensation that subsides following a rest period. Due to predominantly extensive experience in football, elite football players may become accustomed to daily cognitive stressors, or the tasks completed may be too brief compared to the protocols that have been applied in studies to mental fatigue. Conversely mental fatigue may be more prevalent in environments where football is accompanied by additional commitments (full time work/education). The previous research inducing mental fatigue immediately prior to task performance may also be an irrelevant time period where mental fatigue is experienced in elite settings, likely due to high arousal induced by caffeine intake, listening to music and the players general intrinsic motivation to

play. Future research is required to investigate the impact of other time periods (e.g. latter stages of a match, 24 hours post-match) and longitudinal durations (i.e. daily monitoring throughout a season) and subsequent risk of mental fatigue.

1 – INTRODUCTION

1.1 - Background

Mental fatigue is a psychobiological state experienced following exposure to cognitively demanding tasks (Boksem, Meijman & Lorist, 2005; Lorist, Boksem & Ridderinkhof, 2005). Following the first study to measure the impact of prolonged exposure to cognitive activity on performance decrements (Mosso, 1891), research has examined the impact of mental fatigue in travel (Borghini, Astolfi, Vecchiato et al. 2014; Zhao, Zhao, Liu et al. 2012; Hankins & Wilson, 1998), work environments (Åkerstedt et al. 2004; Grandjean, 1979) and education (Winch, 1912). More recently, research has investigated the impact of mental fatigue in sport and exercise performance. Since the first known study (Marcora et al. 2009), three literature reviews have discussed the effects of acute mental fatigue in sport and exercise. The first review (analysing studies up to 2014) revealed that exposure to acute mental fatigue ranging from as little as 3-min 40 seconds up to 90-min had a detrimental effect on physical performance (Silva-Junior et al. 2016). A more recent review (which analysed articles up to April 2016) reported that induced mental fatigue impaired endurance performance (via greater test completion time and decreased time to exhaustion and self-selected power output), but did not significantly impact anaerobic, power or maximal strength performance (van Cutsem et al. 2017). Furthermore, mental fatigue did not affect physiological endurance exercise variables including heart rate, cardiac output, oxygen uptake, maximal aerobic capacity and blood lactate. A subsequent meta-analysis and systematic review concluded that whilst mental fatigue impacted on physical performance, the heterogeneity of the data showed that differences are likely due to random error (McMorris et al. 2018).

Several studies have investigated the effects of induced mental fatigue on team sport performance (REFS). These studies have highlighted the role of cognitive skills required for sport performance. Indeed, it was suggested that with the exception of military combat, team sport performance is more cognitively demanding than any other physical activity (Walsh, 2014). This has since led to research in basketball (Moreira et al., 2018), handball (Penna et al., 2018), cricket (Veness et al., 2017), and association football (soccer) (Coutinho et al., 2018; Coutinho et al., 2017; Smith et al., 2017; Badin, Smith, Conte et al., 2016; Smith et al., 2016a; Smith et al., 2016b) which examined the influence of cognitive fatigue on various aspects of performance. Despite this research interest, the real-life cognitive demands of sporting activity remain unknown. Further work has postulated that several cognitive stressors related to football match-play (prolonged vigilance, decision-making, constantly receiving and processing information in a dynamic environment) and lifestyle factors (expectations from coaches, supporters, sponsors and the media) result in mental fatigue (Coutts, 2016). At present, six original investigative studies measuring the impact of mental fatigue on football-specific performance have been conducted. Three investigated the effects of induced mental fatigue in match-play settings (small-sided games), which have found unclear effects on physical performance (distance covered per minute and the number of accelerations and decelerations) (Coutinho et al., 2017), likely negative effects for technical performance (match involvement, match possession, tackle success) (Badin et al., 2016), plus reductions in tactical performance (i.e. team synchronisation) (Coutinho et al., 2018). Negative effects of mental fatigue were also reported in three laboratory studies which measured football-specific skill performance in Loughborough Soccer Shooting Test (LSST) and Loughborough Soccer Passing Test (LSPT) (Smith et al., 2017, Smith et al., 2016) and visual search behaviour in a football-specific decision-making test (Smith et al., 2016).

1.2 - Research problem

All but one of the research articles investigating the role of mental fatigue in football performance have used either a computerised (Coutinho et al., 2018; Badin et al., 2016) or pen-and-paper (Smith et al., 2017; Smith et al., 2016a; Smith et al., 2016b) version of the 30-min modified Stroop task (Stroop, 1935) to induce mental fatigue. The other study used a more sport-specific 20-min motor task (that consisted of juggling a tennis ball whilst completing agility ladders, and incorporated motor coordination, sustained attention, cognitive processing and perceptual skills) to induce mental fatigue (Coutinho et al., 2017). Such protocols unlikely resemble the cognitive demands experienced in football-specific settings, and could also induce boredom as well as mental fatigue. Moreover, the cohorts in these studies consist of recreational or sub-elite level football players, making it difficult to transfer the findings to elite settings which carry greater pressure (internal and external expectation to succeed) and intensity (frequent fixture congestion and travel demands). Therefore, there is a requirement to challenge and critically evaluate the current methodology adopted in mental fatigue in football research and understand the real-life cognitive demands experienced by elite football players. Indeed, the development of mentally fatiguing tasks with high ecological validity is essential for determining the extent to which mental fatigue occurs in elite football (Carling et al., 2018).

1.3 - Aims of the thesis

The primary aims of the thesis are threefold. Firstly, the thesis aims to examine the current mental fatigue in football literature and critically evaluate the existing methodological practice. Next, perceptions of mental fatigue and boredom following the most commonly used method of inducing mental fatigue (30-min modified Stroop task) will be measured in attempt to distinguish between mental fatigue and boredom, which has been under-researched (Pattyn et al., 2008). This study will also examine post-task mental fatigue to understand its residual effects (i.e. in order to elucidate if mental fatigue is acute or chronic). Lastly, the thesis will investigate the lifestyle and football-related cognitive demands and perceived presence of mental fatigue in professional male, elite academy and elite female football players. It is anticipated that findings from this thesis will lead to a greater understanding of the existence of mental fatigue in elite football and the development of more ecologically valid tasks to induce mental fatigue in subsequent football research.

2 – LITERATURE REVIEW

2.1 - Introduction

Mental fatigue is a psychobiological state experienced following exposure to cognitively demanding tasks (Boksem et al., 2005; Lorist et al., 2005). Feelings of tiredness and a reduction in energy are typically associated with mental fatigue (Boksem & Tops, 2008). Mental fatigue has been shown to impair attention (Chaudhuri & Behan, 2004), task planning (van der Linden, Frese & Meijman, 2013) reaction times (Boksem et al., 2005) and speed of adjustments to task performance after errors (Lorist et al., 2005). The literature investigating the effects of mental fatigue on human performance dates to the late nineteenth century (Mosso, 1891) in the book 'La Fatica'. In this simple study, it was shown that muscular endurance of the index finger was reduced following oral examinations and lectures delivered by two Physiology lecturers. More recent work has since examined the impact of mental fatigue on tasks such as (but not limited to) car driving and long haul aircraft flights (Borghini et al., 2014; Zhao et al., 2012; Hankins & Wilson, 1998), daily working activities (Åkerstedt et al., 2004; Grandjean, 1979) education (Winch, 1912), and sport and exercise performance (McMorris et al., 2018; van Cutsem et al., 2017; Silva Junior et al., 2016).

2.2 - Mechanisms of mental fatigue

It is firstly important to understand the mechanisms of mental fatigue in order to reduce or even prevent its occurrence. In recent years, researchers have theorised several mechanisms of mental fatigue related to biological and personality factors. Four proposed mechanisms of mental fatigue are outlined below.

Dopamine and adenosine

Dopamine is an important neurotransmitter that influences high order cognitive processes (Nieoullon, 2002), and the release of adenosine inhibits dopamine release (Davis et al., 2003). Pageaux et al., (2014) first postulated that changes in dopamine and adenosine concentrations in the anterior cingulate cortex (ACC) cause subjective feelings of mental fatigue. It has been theorised that during demanding cognitive tasks, extracellular cerebral adenosine accumulates within active regions of the brain. It has been suggested that adenosine acts in two ways: by increasing perception of effort during task performance, and impairing motivation by interaction with dopamine in the ACC (Martin et al., 2018). However, as these theories have not been measured in-vivo, the level of evidence to definitively link mental fatigue to dopamine and adenosine concentrations remains low.

Locus-coeruleus norepinephrine system

The locus-coeruleus norepinephrine (LC-NE) system is also suggested to be responsible for the development of mental fatigue (van der Linden, 2011). The LC-NE is a region of the brain responsible for central norepinephrine levels (Aston-Jones, Ratjkowski & Cohen, 1999). Norepinephrine is seen as a neuromodulator for arousal, which Aston-Jones & Cohen (2005) describe as readiness of the brain for perceptual input. Studies have shown that pharmaceutical agents that raise norepinephrine levels reduce fatigue (Stahl, 2002). In addition, indirect measures of mental fatigue (electroencephalography, pupil diameter) have suggested a link between the LC-NE and mental fatigue (van der Linden, 2011; Aston-Jones & Cohen, 2005; Nieuwenhuis, Aston-Jones & Cohen, 2005).

Reward

It has also been proposed that feelings of mental fatigue are influenced by the perceived evaluation of the effort/reward related to the task (Boksem & Tops, 2008), meaning that a high effort/low reward task can be subjectively more mentally demanding than a high effort/high reward task. Indeed, it has been found that a short period of high effort/low reward activity is subjectively more mentally fatiguing than a significantly longer time period of high effort/high reward task action (Park et al., 2001; Sparks et al., 1997). According to this theory, low-ability individuals would be able to match high-ability individuals in a task if superior motivation is channelled into the task, but this comes at a greater cost of fatigue to the low-ability individual. In a sporting context, athletes that are highly intrinsically motivated could be able to match the performance levels of higher-skilled athletes with reduced motivation levels but expend more energy in the process.

Personality traits

It has been postulated that common character traits such as high perfectionism and neuroticism may provide a greater resistance to fatigue (Johnson et al., 1996; Prins et al., 2006; Magnusson et al., 1996; White & Schweitzer, 2000). Boksem & Tops (2008) stated in reference to these personality types that "*these people just do not know when to quit; either because they set their goals too high, are afraid that their achievements will not be perceived as up to the mark by others, or because they are more concerned with being punished for bad results than with being rewarded for good results*". Such theories may transfer to the difference in performance levels between elite and non-elite individuals. It has been demonstrated that induced mental fatigue negatively influenced cycling performance in non-elite cyclists, but elite cyclists were able to attenuate performance levels (Martin et al., 2016). Taken together, experienced elite performers who are extremely driven may be less prone to the potential effects of mental fatigue.

Summary

Several mechanisms have been reported to explain the occurrence of mental fatigue. The variation in mechanisms and difficulty in conducting in-vivo studies to provide evidence to theory (i.e. dopamine and adenosine, LC-NE system) confirms the complexity in understanding how individuals experience mental fatigue and which cognitive tasks induce mental fatigue. Indeed, reward and personality traits likely reduce the impact of mental fatigue, however further applied research in relevant settings is required. The following section of the literature review will provide an overview of the current tasks employed to induce mental fatigue.

2.3 - Inducing mental fatigue

In the mental fatigue literature, several paper and computer-based tasks have been used to induce mental fatigue. These activities differ in duration and task demands. To evoke mental fatigue in research, it is necessary to use a task which provides the required cognitive stimulus. Conversely in applied settings to prevent mental fatigue before competition, it is essential to understand which tasks are cognitively demanding enough to elicit mental fatigue. The following section will outline five cognitive activities that have induced mental fatigue in the present literature, followed by a summarisation of their validity in inducing mental fatigue.

Modified Stroop task

The modified Stroop task is a response inhibition/sustained attention task, and the most commonly used method of inducing mental fatigue. Engagement in a modified Stroop task elevates the activation of the ACC and dorsolateral prefrontal cortex (DL-PFC), which are collectively responsible for attention, decision-making and cognitive flexibility (Banich et al., 2015; MacDonald, Cohen, Stenger et al., 2000). In this task, coloured words ("red", "blue", "green" and "yellow") are presented in a repeated fashion, and participants must identify the colour of the word, ignoring the meaning of the word itself. For example, if the word is presented as "yellow", but in green font, the correct answer would be "green". To increase task difficulty and response inhibition requirements, when a word is presented in red ink the correct response corresponds to the meaning of the word (e.g. if "blue" is written in red font, the correct answer is "blue" and not "red"), making the test a "modified" Stroop task. In the sport and exercise science literature, a modified Stroop task is completed continuously either on a computer or via a paper-based version for 30-min (Smith et al., 2018; van Cutsem et al., 2017).

AX-Continuous Performance Task

The AX-Continuous Performance Task (AX-CPT) is a cognitive control task which examines context processing and goal maintenance, and activates the DL-PFC, which is related to working memory and goal maintenance (Lopez-Garcia, Lesh, Salo et al., 2016). In this task, participants sit in front of a computer screen with individual letters of the alphabet randomly presented (except for K and Y based on their resemblance to X) for 30 ms with a 1200 ms interval, immediately followed by a new letter. When the letter A is followed by the letter X, participants must press the right-sided button, whereas any other two letter orders requires the left-sided button to be pressed (based on a right handed participant). The remaining letters of the alphabet are presented on the screen to serve as invalid cues and non-target probes. A beep sounds for missed or incorrect responses as a prompt to increase speed and accuracy. This task has been adopted in several mental fatigue in endurance performance studies, each lasting 90-min (Smith et al., 2015; MacMahon et al., 2014, Marcora et al., 2009).

Eriksen Flanker Test

The Eriksen Flanker Test is a response inhibition task predominantly engaging the DL-PFC and dorsal anterior cingulate cortex (dACC) (Blasi, Goldberg, Weickert et al., 2006), which requires a fast and accurate recognition of alphabetic letters. Participants are placed in front of a computer screen and presented with a horizontal row of three uppercase letters. In previous mental fatigue studies using continuous two-hour protocols (Faber et al., 2012; Lorist et al., 2005), the central letter is the target, whilst the remaining letters act as "flankers". When the central letter is an S, participants must quickly respond by pressing the button situated in their right hand, and conversely when the central letter is an H, a quick response is required with the left hand. Each row of letters remains on the screen for a maximum period of 1200 ms, and if the initial response is incorrect, participants are provided with an additional 500 ms to select an alternative response. To increase task difficulty, the target letter is presented in green on a black background for 50% of the trials, and in red during the remaining 50% of the trials. In addition, the "flankers" have the same identity and colour as the target letter during 50% of the trials (HHH or SSS), whilst in the other half of the trials, flankers have a different identity and colour than the target letter (e.g. SHS or HSH). A pre-cue of 150 ms is also displayed 1000 ms before the row of letters, denoting the response hand (left and right) or colour (red and green).

Sustained Attention to Response Task

The Sustained Attention to Response Task (SART) is a response inhibition task which has induced mental fatigue in military personnel using 4 x 10-min blocks (Dillard et al., 2017). Sustained attention tasks have been shown to increase alpha brain activity, which denotes an impairment in attention and increase in drowsiness (Okogbaa et al., 1994). In an SART, participants are placed on a chair and are presented with a single digit (1-9) placed on the screen in front of them. The participant must correspond the number on the screen with the number on the keypad in front of them (e.g. tapping the number 1 keypad button when number 1 is presented on the screen), except for the number 3, which must be ignored. Each number is shown on screen for 250 ms and is followed by a 900 ms mask. The numbers are presented in the same font, but the font size varies between 48, 72, 94, 100, and 120 mm, along with a variation in the height of the font (12 and 29 mm). Response times are measured in the SART, and penalties occur for inappropriately responding to 'No-Go' stimuli and inappropriately withholding response to 'Go' stimuli.

Go/NoGo task

The Go/NoGo is a response inhibition task which requires fast reaction times and response accuracy. The ACC and prefrontal cortex (PFC) have been shown to be highly active during a Go/NoGo task, which suggests the role of attention, planning complex cognitive behaviour and decision-making (Menon, Adleman, White et al., 2001). In a Go/NoGo test, participants are seated in a dimly lit room with a keypad placed in both hands. On a screen located in front of the participant, four different types of stimulus are presented individually, consisting of "Go left", "Go right", "NoGo left" and "NoGo right". When presented with "Go left" or "Go right", participants must press the corresponding keypad button in reaction to the stimulus (e.g. using the left handed keypad to confirm "Go left"), whereas a "NoGo left" or "NoGo right" stimulus must be ignored. The left and right stimuli are randomly presented in an equal fashion, and participants are encouraged to respond to the stimuli as quickly and accurately as possible. The Go/NoGo task has previously induced mental fatigue in a general healthy population using a 60-min protocol (Kato et al., 2009).

Summary

Several computer/paper based tasks have been used to induce mental fatigue in the literature. Each have a shared purpose of providing varying task complexity (i.e. congruent/incongruent trials) to increase brain activity and induce mental fatigue. Whilst validated and simple to administer, a shared limitation of these tasks is their prolonged repetitive nature, which is often irrelevant to real-life tasks. Indeed, low contextual interference tasks (i.e. repetitive and predictable tasks) are not as cognitively engaging as high contextual interference tasks (i.e. unpredictable with constantly changing challenges) (Lelis-Torres et al., 2017), and likely provides a cognitive "underload" (Pattyn et al., 2008). Compared to "overload" tasks (i.e. high cognitive engagement), an "underload" task provides a reduced cognitive challenge and is associated with mind wandering (i.e. boredom) (Pattyn et al., 2008). Whilst the aforementioned computer tasks used to induce mental fatigue may resemble some real-world tasks with prolonged vigilance and low cognitive engagement (i.e. repetitive factory or office-based tasks), more dynamic tasks (e.g. sport and exercise) require a more ecologically valid protocol to induce mental fatigue in future studies. Therefore, further research is necessary to understand real-life mentally fatiguing tasks to increase ecological validity in various settings.

2.4 - Measuring mental fatigue

Mental fatigue can be assessed using several different indicators (performance, psychological or physiological). Being able to measure mental fatigue aids the understanding of the cognitive demands of selected tasks, which can then aid research and practice. The available methods of inducing mental fatigue are discussed below.

Electroencephalography

One of the most commonly utilised method used to assess mental fatigue is electroencephalography (EEG), which measures spontaneous electrical brain activity in four regions of the brain - delta, theta, alpha and beta (Teplan, 2002). The existence of electrical currents in the brain was discovered in 1875 by English physician Richard Caton, who initially observed the EEG from the exposed brains of animals (Teplan, 2002). A typical EEG measurement consists of a cap worn on the scalp with electrodes connected on up to 128 channels, amplifiers which allow for the signals to be read, a converter change data from analogue to digital, and a personal computer for data storage and display (Teplan, 2002). The technology remains predominantly wired, but wireless technology is also available and increasingly developing (Berka, Levendowski, Cvetinovic et al., 2004). The use of EEG has shown high test retest reliability when measuring brain activity during cognitive tasks (McEvoy, Smith & Gevins, 2000).

The tasks which are measured using EEG are predominantly static in nature, and have consisted of driving (Zhao et al., 2012; Ting, Hwang, Doong et al., 2008; Lal & Craig, 2002) and computer-based vigilance tasks (Berka, Levendowski, Lumicao et al., 2007; Berka, Levendowski, Cvetinovic et al., 2004; Gevins, Smith, Leong et al, 1998). Conducting studies which incorporate physical activity proves difficult due to light disturbances, sweat, noise and excessive movement, which can negatively influence the strength of the EEG signal, which is critical to the quality of the data collection (Britton, 2016; Reinecke, Cordes, Lerch et al., 2011). Nevertheless, EEG has been used to measure brain activity in treadmill endurance performance (Brownsberger et al., 2013), knee extension exercises (Baumeister, Reinecke, Schubert, Schade & Weiss, 2012), golf (Reinecke, Cordes, Lerch et al, 2011; Baumeister, Reinecke, Liesen, & Weiss, 2008), and physically active computer games (Baumeister, Reinecke, Cordes, Lerch, & Weiss 2010). Technological advances are likely required to accommodate for activities with greater physical task demands (i.e. team sports). Recent research has adopted glasses with built-in EEG technology that acquires movement of the pupil and blinking from the light reflected from the eye, but presented mixed results in measuring brain activity in a cognitive task (Sampei et al., 2016).

Functional Near-Infrared Spectroscopy

Functional Near-Infrared Spectroscopy (fNIRS) is a haemodynamic-based technique which assesses functional activity in the brain (Hoshi, 2003). Typically, optodes (a sensor device) are placed on the skin over the PFC to measure blood oxygenation during cognitive tasks (Xu et al., 2017; Mehta & Parasuraman, 2014). Previous research using fNIRS has demonstrated the accumulation of mental fatigue during prolonged driving activity (Gao, Pan, Li, & Li 2016), and has also been incorporated in conjunction with EEG (Nguyen, Ahn, Jang et al., 2017; Aghajani & Garbey, 2017), and with both EEG and Electrocardiogram (ECG) readings to measure mental fatigue (Ahn, Nguyen, Jang et al., 2016). Despite the low amount of research utilising this method, fNIRS may be a desirable option to assess mental fatigue given its portability, wireless capability, use in real-world settings and low cost (Mehta et al., 2016).

Heart rate variability

Heart rate variability (HRV) has been measured in several studies investigating cognitive load in task performance. During flight simulation, significantly increased heart rates were only recorded for long haul pilots during the take-off and landing phases of the journey (Hankins & Wilson, 1998). Research in simulated office working environments has demonstrated an increased heart rate frequency with increased mental workload and stress (Taelman et al., 2011; Hjortskov et al., 2004; Garde et al., 2002). Despite these findings, caution must be noted when using heart rate as an indicator of mental workload in isolation. Further work showed that monitoring traffic density in a busy city elicited greater heart frequencies during periods of higher traffic flow, irrespective of shift pattern, and was correlated with increases in stress and mental fatigue (Fallahi et al., 2016).

Pupillary response

In pupillary response monitoring, video analysis captures changes in pupil diameter under exposure to cognitive tasks. An increased pupil diameter has been recorded for individuals exposed to prolonged cognitive tasks such as reading text (Yong, Guo'en, & Yanli, 2004), truck driving (Morad et al., 2009) and piloting (LeDuc et al., 2005). This method is a non-invasive, cost effective and portable tool which is simple to administer. However, as pupil diameter can be influenced by many different factors (e.g. light, arousal, sleep duration), it is recommended that this approach is measured in conjunction with other physiological measurements of mental fatigue (e.g. fNIRS, EEG).

Galvanic skin response

Galvanic skin response represents a change in electrical resistance in the skin when exposed to emotional stressors. It is most commonly associated with lie detector (polygraph) tests (Hovarth, 1979), but has long been utilised to measure the mental effort exerted in a cognitive task (Geldreich, 1941; Nourbakhsh, Chen, Wang, & Calvo, 2017; Widyanti et al., 2017). The readings from galvanic skin response have established correlations between the effect of stressors and cognitive functions (McEwen & Sapolsky, 1995). This method has been found to cost effective, but less effective in comparing varying levels of mental workload in comparison to HRV and NASA-TLX (Widyanti et al., 2017), suggesting a limited ability to measure mental fatigue. An explanation of this finding was not discussed in the study, but like aforementioned measurements of mental fatigue, using galvanic skin response to determine mental fatigue in isolation should be met with caution due to the potential influence of other emotions such as anxiety or stress.

Task performance

General cognitive tasks

It has been suggested that task performance is the gold standard measurement of mental fatigue (Hockey, 2011). Indeed, research has shown that reaction times are impaired by time on task. In one study (Lorist et al., 2005), 15 participants performed a 2-hour Eriksen Flanker test and showed a significantly greater decline in reaction times during the final 30-min period in comparison to the initial 90-min of the task. In further work using a 3-hour continuous sustained attention task, it was demonstrated that when the task time was broken down into four separate periods (4 x 45-min), there was a linear increase in reaction times and percentage of targets missed (Boksem et al., 2005). Similar trends were reported following a 50-min auditory task (Moore, Key, Thelen, & Hornsby, 2017), with higher reaction times and lower response accuracy in the final 25-min of the activity. This was also accompanied by subjective data which reported a decline in motivation to complete the task and attention on the task. In comparison to the more expensive and complex measures (e.g.

EEG), task performance is an inexpensive and simple to administer method of measuring task performance.

Auditory mental fatigue

Prolonged listening in various environments (e.g. presentations, meetings and classes) may be considered tiring, despite one often being seated and not seemingly expending energy. Indeed, one must sustain attention and inhibit alternative actions (i.e. focussing attention on another activity) much like the demands of cognitive tasks such as the AX-CPT. Only recently has sustained listening and its impact on arousal and mental fatigue been investigated in normal hearing populations. In one study (McGarrigle, Dawes, Stewart, Kuchinsky, & Munro 2017), participants performed a speech-picture verification task in different signal-to-noise ratios (SNRs) while their pupil size was monitored and response times recorded. In the more challenging SNR, a significant increase in pupil diameter was observed in the second half of the trial, suggesting a reduction in physiological arousal. In subsequent research, Moore et al., (2017) incorporated a 50-min auditory choice task, quantifying mental fatigue using subjective (self-report) and behavioural (response time and accuracy) measures, as well as event-related potential (ERP) measures indexing motivation and general arousal. The ERPs revealed changes in neural activity consistent with decreased arousal. The decrease in arousal revealed a significant, positive correlation with subjective report of reduced motivation. These studies are limited by the relevance of the auditory tasks to real-life situations. Future work is required in more ecologically valid settings (e.g. replicated meetings or relevant classes/lectures).

Car driving

Several studies have highlighted the impact of monotonous driving protocols on subjective and objective measures of mental fatigue. Using EEG, it was found that following 90-min of driving simulation activity, that there was a significant increase in alpha brain activity and a significantly lower decrease in beta brain activity in comparison to baseline levels (Zhao et al., 2012). A rise in alpha brain activity is associated with decreased attention levels, and a reduction in beta brain activity is associated with lower arousal levels (Okogbaa et al., 1994). Further research revealed that up to two hours of monotonous motorway simulation driving caused a significantly greater delta and theta brain activity, suggesting a reduction in alertness (Lal & Craig, 2002). This study also used a Brunel Mood Scale (BRUMS) questionnaire revealing greater subjective trait anxiety, tension–anxiety, fatigue–inertia and reduced vigour–activity. Moreover, long distance driving (90-min) has resulted in greater reports of sleepiness, and decrements in driving performance and reaction times (Ting et al., 2008).

Subjective measures

Despite the simplicity and cost-effective nature of using task performance to measure mental fatigue, its implementation in isolation is unlikely to detect mental fatigue. Indeed, other factors such as incentive and motivation can impact on the variation in task performance levels (Brown & Bray, 2017; van der Linden, 2011), which necessitates the use of further measures to understand individual variation in fatigue. The following section will examine three subjective measurements of mental fatigue.

Profile of Mood State & Brunel Mood Scale

The Profile of Mood State (POMS) is a valid and reliable psychometric questionnaire that consists of 65 adjectives (e.g. annoyed, confused, depressed, exhausted, anxious, active) rated on a five-point

Likert scale (0 = not at all, 1 = a little, 2 = moderately, 3 = quite a bit, 4 = extremely) (McNair et al., 1985). The Brunel Mood Scale (BRUMS) questionnaire is a reduced version of the POMS that contains 24 items divided into the same six respective sub-categories as the POMS, as well as the same five-point Likert scale and scoring system (Terry, Lane & Fogarty, 2003). Mental fatigue has been measured using the POMS (Martin, Thompson, Keegan, Ball, & Rattray 2015; MacMahon et al., 2014; Suzuki et al., 2004) and BRUMS (Smith et al., 2015; Rozand et al., 2014; Pageaux et al., 2014; Pageaux et al., 2013; Marcora et al., 2009), however the measurement of fatigue is general (i.e. assesses "tiredness"), and therefore unable distinguish between physical and mental fatigue.

Visual Analogue Scale

The visual analogue scale (VAS) is a valid and reliable method of measuring fatigue (Lee, Hicks & Nino-Murcia, 1991) and has measured mental fatigue in previous sport and exercise science research (Smith et al., 2018; van Cutsem et al., 2017). When using a VAS, participants are presented with a statement (e.g. "I am mentally fatigued") or a question (e.g. "How mentally fatigued are you?") and instructed to use a 0 – 100 mm scale to denote their answer, with 0 being a minimal value (i.e. no mental fatigue) and 100 being maximal (extremely mentally fatigued). This can be conducted using a 0 – 100 numerical slider scale on an electronic device (i.e. tablet) or by using a pen to draw a vertical line on a 100 mm horizontal line on paper. The VAS is cheap and simple to administer, but caution is advised when using terms that participants are not aware of. Indeed, the term "mental fatigue" is challenging to define, and research participants may misinterpret it with similar constructs such (e.g. boredom, sleepiness, physical fatigue), making the use of clear definitions imperative in study designs.

Summary

Several methods have been used in the literature to measure mental fatigue. The use of EEG to measure mental fatigue currently has the strongest level of evidence, with several studies demonstrating its suitability to measure brain activity in numerous cognitive tasks. However, EEG has been used in statically situated activities with minimal movement and perspiration (i.e. general cognitive tasks and driving protocols) in order to minimalise the quality of the signal. In addition to lengthy setup times and wired technology, these are limitations which are difficult to overcome in dynamic activities (i.e. football), which in ecologically valid settings requires excessive movement and results in perspiration. However, due to the limited available evidence, further research is required to determine the efficacy of using physiological measures such as fNIRS, HRV, pupillary response and galvanic skin response for measuring mental fatigue. Furthermore, changes in brain, heart and skin function may only be partially explained by mental fatigue and are likely related to other factors such as stress, arousal and physical fatigue.

Conversely, task performance and psychological measurements are simpler to implement. Due to a greater sensitivity in subject response (0-100 mm) and ability to directly query perceived mental fatigue, the VAS is a more accurate psychological measuring tool than the POMS and BRUMS, which measure fatigue in a general sense. However, when implementing a VAS, a clear definition of mental fatigue must be provided to participants to ensure the understanding of the term. Task performance is advocated as a measurement of mental fatigue, but further research (i.e. similar to current driving research) is required to measure task performance which is relevant to the population of the study (e.g. a sport-specific task for an athlete). However, in isolation both measurement tools are limited in their ability to accurately identify mental fatigue due to additional factors such as reduced motivation, boredom or other changes in mental state. It is recommended that a variety of simultaneous methods (e.g. EEG, ecologically valid task performance and VAS) are used to measure mental fatigue in order to separate the construct from physical fatigue and emotional states. Indeed, using all three measuring tools takes additional time to implement (i.e. set-up times as well as task duration), and will often prove challenging to conduct in future research.

2.5 - Reducing mental fatigue

With the recent increase in mental fatigue literature, research is beginning to understand solutions to reduce the effects of mental fatigue on physical and cognitive performance. This concept is important in applied sporting settings to understand the impact and practicality of different methods available to prevent or reduce feelings of mental fatigue. The following section will discuss the effects of brain endurance training, caffeine supplementation and financial incentive.

Brain Endurance Training

One novel concept of increasing endurance performance is to incorporate the simultaneous completion of prolonged cognitive tasks alongside physical training. This was investigated in recent research which created a novel training method called "brain endurance training" (BET) (Marcora, Staiano, & Merlin, 2015). Subjects (n=35) cycled at 60% of VO_2 max for 60-min, 3 times a week for 12 weeks. The subjects were randomly split into two groups, which consisted of a BET group who completed a cognitively demanding task on a computer (AX-CPT) whilst completing all the cycling sessions, plus a control group who only participated in the cycling trials. From the pre- and post-testing results (a time to exhaustion test at 75% VO_2 max), time to exhaustion was significantly longer in the BET group (pre-test 28 ±9 min; mid-test 39 ± 11 min; post-test 55 ± 17 min) compared to the control group (pre-test 18 ± 5 min; mid-test 23 ± 7 min; post-test 28 ± 12 min). Whilst suitable for statically situated activities (i.e. stationary bike, treadmill), the present study design (being seated at a keyboard and focusing on a computer monitor) would be unsuitable for sporting disciplines with more multifaceted physical patterns (i.e. team sports), as the equipment is not portable. Dynamic activities could consider the use of dual task paradigms in future research designs (i.e. sport specific activity interspersed with cognitive problem-solving tasks) to increase cognitive load and allow the brain to adapt to various stimuli and stressors.

Caffeine

Another proposed protective agent against mental fatigue is caffeine consumption. Mechanistically, caffeine inhibits adenosine receptors (Fredholm, 1995), reducing the inhibition of dopamine receptors, which is related to the onset of mental fatigue (Martin et al., 2018). Caffeine has been shown to enhance task switching ability (Einöther et al., 2010), reduce reaction times (Jacobson & Edgley, 1987), and increase arousal (Barry et al., 2005). The demonstrated positive effects of caffeine supplementation may therefore reduce the subjective feelings of mental fatigue and attenuate or even increase physical and cognitive performance levels.

In the first study to test this theory (Azevedo, Silva-Cavalcante, Gualano, Lima-Silva & Bertuzzi, 2016), eight physically active cyclists completed a cycling to exhaustion test at 80% of maximal power output under four different conditions (control, mental fatigue, mental fatigue and caffeine, and mental fatigue and placebo). The selected mental fatigue and control tasks were the AX-CPT test and a nature documentary, respectively (both 90-min duration). Caffeine was administered (5 mg kg^{-1}) to the mental fatigue and caffeine group approximately 90-min before the cycling test. It was shown that the mental fatigue and caffeine condition resulted into a longer time to exhaustion than the control, mental fatigue, and mental fatigue and placebo treatments. The mental fatigue and caffeine condition also significantly increased perceived vigour compared to the control and mental fatigue trials. Aside from oral caffeine ingestion, a recent study measured the impact of a caffeine mouth rinse on mental fatigue (van Cutsem, De Pauw, Marcora, Meeusen, & Roelands, 2018). Ten participants completed a 90-min Stroop task either side of a 3-min Flanker task (before the start of the Stroop and following each 12.5% of the trial), whilst administered a caffeine-maltodextrin mouth rinse or a placebo (artificial saliva). Findings showed an attenuated performance in the Stroop task (significantly greater performance in the final 12.5% of the task) and a significantly lower subjective mental fatigue rating in the caffeine maltodrextrin mouth rinse condition. Further research is required to investigate the effectiveness of caffeine in real-life situations over repeated trials, as chronic caffeine consumption reduces improvements in reaction time and visual vigilance (Judelson et al., 2005).

Financial reward

In addition to cognitive training and ergogenic aids, research has demonstrated that a financial incentive can increase motivation and maintain task performance following exposure to a mentally fatiguing task (Brown & Bray, 2017). Participants (n=82) completed two isometric handgrip trials separated by a 12-min incongruent Stroop task (5 x 2-min blocks with 4 x 30-s rest periods), using a 2 (high cognitive control/low cognitive control) × 2 (incentive/no incentive) design. Whilst mental fatigue was higher in both high cognitive control conditions (high cognitive control/no incentive, high cognitive control/financial incentive), isometric handgrip performance only decreased in the high cognitive control/no incentive trials. These findings showed that financial incentive can attenuate physical performance and alter central drive to motor units. However, caution is advised when interpreting such results in acute settings, which may not replicate physical tasks with a longer duration, which are typically accompanied by more discomfort and fatigue.

Summary

There is a small amount of evidence which has demonstrated an ability to reduce feelings of mental fatigue. The use of BET has been shown to provide cognitive training relevant to decrease the perception of effort and increase endurance performance, however further innovative tools must be developed to prove effective in dynamic tasks which would require wireless technology/protocols. Moreover, there is evidence that a financial incentive attenuates short term physical and cognitive performance, but additional research is required to understand its effectiveness in tasks with greater duration and cognitive complexity/physical strain. Caffeine supplementation is the optimal method to reduce mental fatigue due to its ability to increase arousal and dopamine levels, and attenuate physical and cognitive task performance. The availability of caffeine is widespread, cheap and is produced in different forms to suit individual preference (i.e. drinks, shots, gels, tablets).

2.6 - Mental fatigue and physical performance

In the past decade, many studies have investigated the effects of induced mental fatigue on physical performance. The following section will initially outline the impact of mental fatigue on endurance (cycling, running and swimming) and neuromuscular (endurance and maximal) performance. This will be followed by a consensus on the level of evidence for effects of mental fatigue on each parameter of physical performance discussed.

Impact of mental fatigue on endurance performance

Cycling

Time to exhaustion

In the first known study to assess the effects of mental fatigue on endurance exercise performance (Marcora et al., 2009). Sixteen moderately active subjects cycled to exhaustion at 80% of maximal power output following exposure to a 90-min cognitively demanding (AX-CPT test) or neutral (watching railway and car related documentaries) task. Results from a BRUMS questionnaire found a significantly higher state of subjective mental fatigue following the cognitively demanding task, which significantly reduced time to exhaustion in comparison to the neutral task condition. This was also accompanied by a higher perception of effort during the exercise test. In more recent work, eleven trained cyclists completed two time to exhaustion tests to determine critical power and curvature constant under a mental fatigue (30-min modified Stroop task) and control (30-min of reading magazines) condition (Salam et al., 2018). Perception of effort was significantly higher in the mental fatigue condition, although no significant differences in heart rate or critical power were reported between conditions. Pre-post performance blood lactate measures were significantly lower in the mental fatigue condition, suggesting a reduced physical workload capacity.

Self-paced performance

In the only study of its kind, self-paced cycling performance was examined following an unspecified 90-min unspecified continuous cognitive activity (CCA) task (Brownsberger et al., 2013). In comparison to a control condition (who watched an emotionally neutral documentary), power output was significantly lower during 10-min cycling bouts at fairly light (RPE = 11) and hard (RPE = 15) intensities. Prior to exercise, perceptions of fatigue were significantly higher in the CCA task condition, whilst beta-band activity recorded using EEG was also significantly greater following CCA completion. A rise in beta-band activity is observed under prolonged cognitive tasks (Boksem et al., 2005), potentially being a causation of the feeling of mental fatigue.

Time trial performance

Pires et al., (2018) investigated the effect of mental fatigue on long distance time trial and cognitive performance. Eight recreational cyclists performed a 20-km cycling time trial following either a 30-min rapid visual processing task (mental fatigue) or seated rest (control). The PFC EEG was measured during the rapid visual processing takt and at 10 and 20 km of the cycling time trial. Cyclists in the mental fatigue condition performed 2.7% slower than in the control condition and displayed a higher theta band power during the rapid visual processing task and at 20 km of the cycling time trial. Rating of perceived exertion increased more rapidly in the mental fatigue condition and was accompanied by significantly greater decreases in motivation and felt arousal during the time trial.

Maximal aerobic performance

One recent study has investigated the impact of mental fatigue on cycling performance and cognitive function. In a randomized counterbalanced, 2 × 2 cross-over study, ten junior cyclists completed a cognitive performance test (d2 test) 20 m multistage fitness test to measure VO_2max and velocity at which VO_2max occurs (vVO_2max) under two separate conditions (30-min Stroop task and 30-min reading control task) (Slimani et al., 2018). Subjective ratings of mental fatigue were significantly higher following the Stroop task. Concentration performance and total number of errors in the d2 test, along with vVO_2max, and estimated VO_2max values were all negatively affected by mental fatigue.

Multiple cycling session performance

Research has also examined the impact of mental fatigue when placed between two incremental cycling tests (Vrijkotte et al., 2018). Nine trained cyclists participated in a single blind, randomised, placebo-controlled study, where either a rest period (control) or a computer-based Stroop task (induced mental fatigue) were performed for 90-min in-between two maximal cycling tests. Results showed no differences in cognitive (Eriksen Flanker task) or physical performance (blood lactate, heart rate values and power output) between conditions. However, subjective ratings of mental fatigue (using a VAS), POMS and RPE were significantly higher in the mental fatigue condition. The insignificant difference in physical performance in these trained cyclists across the conditions may be explained by their training status. Previous work by Martin et al., (2016) also showed that the physical performance of elite cyclists was unaffected by a mentally fatiguing task (30-min Stroop task) when compared to non-elite cyclists.

Table 1 – Mental fatigue in cycling

Study	Subjects	Study design	Mentally fatiguing task	Measure of mental fatigue	Exercise	Main findings
Marcora et al., (2009)	16 regular exercisers (m=10, f=6)	Randomised crossover	90-min AX-CPT	BRUMS	Cycling TTE	↑ RPE ↓ TTE
Salam et al., (2018)	11 well trained male cyclists	Randomised crossover	30-min Stroop	10-point scale (1=not at all, and 10=extremely)	Cycling TTE at 40 – 100% of VO_2peak	↑ PE No difference in HR or critical power
Brownsberger et al., (2013)	12 regular exercisers (m=8, f=4)	Randomised crossover	90-min AX-CPT	VAS	10-min self-paced cycling (RPE locked at 11 & 15)	↓ Power output
Pires et al., (2018)	8 recreational male cyclists	Randomised crossover	30-min Rapid Visual Processing Task	EEG Shortened version of the POMS	20-km cycling time trial	↑ EEG theta band power during RVP test ↑ RPE ↓ Time trial performance
Slimani et al., (2018)	10 junior male cyclists	Randomised crossover	30-min Stroop	BRUMS	20 m multistage fitness test	↑ RPE ↓ VO_2max
Vrijkotte et al., (2018)	9 trained male cyclists	Single blind, randomised, placebo controlled	90-min Stroop	POMS	2 x incremental cycling tests	↑ RPE No difference in physical performance

Running

Time trial performance

In the first known study to investigate mental fatigue on running performance (Pageaux et al., 2014), twelve physically active participants completed a 5-km time trial on a treadmill after completing either an incongruent Stroop task involving response inhibition or a congruent Stroop task without response inhibition (control), each lasting 30-min. Although no significant difference in subjective feelings of mental fatigue was found following task completion, 5-km performance was significantly slower in the incongruent Stroop task condition compared to the control condition. The differences in performance could be explained by the greater perception of effort reported by participants during the time trial following the incongruent Stroop task condition.

In a further study, twenty experienced runners completed two 3000 m trials on an indoor under mentally fatiguing (90-min AX-CPT test) and control (90-min documentary) conditions. The 3000 m running performance was significantly slower in the mentally fatiguing condition (MacMahon et al., 2014). Throughout the running trials there were no significant differences in heart rate, blood lactate or RPE. It is therefore unclear as to why performance was impaired in the cognitively demanding task. One suggestion may be that mentally fatigued runners slowed to attain a similar RPE to the control group condition in order to complete the test.

Intermittent running

It has also shown mental fatigue to negatively impair intermittent running performance (Smith, Marcora & Coutts, 2015). Ten team sport athletes performed two self-paced intermittent running trials on a treadmill for 45-min, separated by seven days under a mentally fatiguing (90-min AX-CPT test) or a control task (90-min documentary). Results demonstrated that the mentally fatiguing task reduced the distance covered at low running activity (LIA), but had no significant effects on high intensity activity (HIA) including running distances or peak velocities, which may be explained by the short duration of those intensities, which do not appear to be affected by mental fatigue (van Cutsem et al., 2017). Session RPE (recorded 30-min after the running protocol) was significantly greater in the mentally fatiguing condition, suggesting an influence of mental fatigue on perception of effort whilst running. Subsequent work compared the impact of a high cognitive load (incongruent Stroop task) and a low cognitive load task (congruent Stroop task) on beep test performance in 13 active athletes (MacMahon, Hawkins & Schücker, 2019). It was shown that participants dropped out of the beep test earlier in the high cognitive load task, with no difference between conditions for heart rate and motivation.

Table 2 – Mental fatigue in running.

Study	Subjects	Study design	Mentally fatiguing task	Measure of mental fatigue	Exercise	Results
Pageaux et al., (2014)	12 physically active subjects (m=8, f=4)	Randomised crossover	30-min Stroop (paper)	BRUMS	5-km running time trial	↑ RPE ↓ Average running speed
MacMahon et al., (2014)	20 experienced runners (m=18, f=2)	Randomised crossover	90-min AX-CPT	POMS	3-km running time trial	↓ Average running speed No difference in RPE
Smith et al., (2015)	10 male team sport players	Randomised crossover	90-min AX-CPT	BRUMS	45-min intermittent running protocol	↓ LIA velocity No difference in HIA or RPE

Swimming

The impact of mental fatigue on swimming performance is presently limited to one known study. Penna et al., (2018) investigated the influence of mentally fatiguing task (30-min Stroop Colour Word Test) on subjective markers of mental fatigue, heart rate variability and swimming performance (1500 m time trial) in 16 experienced junior swimmers. Compared to a control condition (watching an emotionally neutral video for 30-min), the Stroop Colour Word Test reported significantly greater levels of mental fatigue and mental effort. Time trial performance was 1.2% slower in the mental fatigue condition, despite no significant differences between trials for rating of perceived exertion and heart rate variability. Whilst a decrease of 1.2% in performance appears small, this is greater than the differences (0.72 s) which separated the three medallists in the 1500 m Rio 2016 Olympic final (Penna et al., 2018). This evidence shows that mental fatigue can elicit negative alterations in performance which may significantly impact on competition outcome.

2.7 - Impact of mental fatigue on neuromuscular activity

Neuromuscular endurance performance

Three studies have investigated the impact of mental fatigue on neuromuscular endurance performance, with varied findings. In the first known investigation (Bray, Martin, Hicks & Woodgate 2008), forty nine sedentary undergraduates performed an isometric endurance task (a maximum endurance isometric contraction of their dominant hand at 50% of their maximal voluntary contraction (MVC) using an isometric handgrip dynamometer) following exposure to either an unmatched or matched Stroop test. Following a brief exposure to the tasks (3-min 40 s), it was found that the unmatched Stroop task condition caused a significantly greater degradation in performance and an increased EMG activity in comparison to the matched Stroop task condition. In later research (Pageaux et al., 2013), ten participants performed a single prolonged submaximal contraction of the knee extensors (20% MVC) until exhaustion, under either a 90-min mentally fatiguing or time matched control task (wildlife documentary) condition. Following the endurance task, no significant differences were found for the decline in MVC torque, voluntary activation level or peripheral parameters of neuromuscular function. However, RPE (measured every 20 s) was found to be significantly higher in the mentally fatiguing condition. In additional work (Pageaux et al., 2015), twelve participants performed a mentally fatiguing task (incongruent Stroop task) or control task (congruent Stroop task) for 30-min. Following the task condition, participants cycled for 6-min at 80% of their maximal power output. The results showed that whilst the mentally fatiguing condition significantly raised the RPE during the cycling task, no significant differences were reported for MVC torque, maximal voluntary activation or resting twitch. It is possible that the endurance task was too short for the altered perception of effort to have a negative influence on physical performance.

Maximal neuromuscular performance

Other work has investigated the effects of a longer exposure (22-min) of the modified Stroop task on MVC during handgrip exercise (Bray, Graham, Martin & Hicks, 2011). Following 1-min of the modified Stroop task and at the end of 7 x 3-min intervals, participants performed a 4 s handgrip squeeze using a hand dynamometer. A significant decline in linear force production in handgrip performance was found compared to the control condition (matched Stroop task), which was accompanied by significantly higher ratings of perceived mental exertion. Although this early work has provided evidence on the effects of mental fatigue on neuromuscular task performance, the small musculature examined (muscles of the hand) creates a difficulty in translating the results into whole body performance (i.e. running, cycling etc). In contrast, recent research has demonstrated that a mentally fatiguing task does not affect maximal muscle activation (Rozand et al., 2014). In this study, ten subjects performed 10 intermittent maximal voluntary contractions of the knee extensors (duration – 4 s) under three contrasting levels of mental exertion each lasting 27-min; high mental fatigue (incongruent Stroop task), medium mental fatigue (congruent Stroop task) and low mental fatigue (watching a movie). No significant differences in maximal voluntary torque and force production were found between the three conditions. These findings may be explained by the brief nature of the performance task, where the central nervous system is able to fully recruit for such a short period of time.

Table 3 – Mental fatigue and neuromuscular performance

Study	Subjects	Study design	Mentally fatiguing task	Measure of mental fatigue	Exercise	Results
Bray et al., (2008)	49 sedentary undergraduate students	Randomised crossover	3-min 40 second Stroop	7-point Likert scale	Isometric endurance task (50% MVC)	↓ Isometric endurance performance ↑ EMG activity
Pageaux et al., (2013)	10 (no description of the cohort)	Randomised crossover	90-min AX-CPT	BRUMS	Submaximal contraction of the knee extensors (20% MVC)	↓ MVC torque ↑ RPE
Pageaux et al., (2015)	12 (no description of the cohort)	Randomised crossover	30-min Stroop	BRUMS	6-min cycling at 80% MPO	↑ RPE No differences in MVC torque and maximal voluntary activation
Bray et al., (2011)	38 undergraduate students (m=25, f=13)	Randomised crossover	22-min Stroop	VAS	4-s maximal handgrip squeeze	↓ Linear force production ↑ RPE
Rozand et al., (2014)	10 active males	Randomised crossover	27-min Stroop (paper)	BRUMS	4-s maximal handgrip squeeze	No difference in 4-s MVC

Summary

Research has generally demonstrated a negative impact of induced mental fatigue on physical performance. Mental fatigue impairs time to exhaustion, self-paced, time trial and maximal aerobic performance in cycling, time trial and low intensity running performance in running, swimming time trial performance, yet has limited impact on submaximal and maximal neuromuscular performance. The negative impact of mental fatigue is more prevalent in steady state physical tasks with longer durations as opposed to acute activities (i.e. MVC). This is likely due to the greater RPE values reported in endurance studies by individuals in a mental fatigue condition group. Indeed, a task with short duration (4 s MVC) may be too brief to be affected by mental fatigue, as motivation is high enough to complete the short task. Future research is required in more maximal performance tasks with greater relevance to sport and exercise (i.e. a weightlifting exercise as opposed to a handgrip dynamometer test). Ecological validity must also be considered for the choice of cognitive task used before the performance test, as it is unlikely the cognitive demands of the Stroop task would reflect the cognitive activities engaged by an athlete in the lead up to competition.

2.8 - Impact of mental fatigue on sport-specific performance

Along with physical running demands, both individual and team sports consist of technical demands that promotes frequent complex decision-making activities throughout a match (Vickery et al., 2018; Carling & Dupont 2011, Rampinini, Impellizzeri, Castagna, Coutts & Wisløff, 2009). Some (but not all) research has suggested that physical fatigue can negatively impact on technical performance. In team sports, technical involvements in rugby league appear to be influenced by match-related fatigue, along with a similar impact on passing ability in young football players (Rampinini et al., 2008). Furthermore, research has demonstrated that physical fatigue negative impacts technical performance in tennis (Davey, Thorpe & Williams, 2010). It was previously suggested that physical and technical decline in matches is predominantly attributed to physical fatigue (Rampinini et al., 2008), but with the rise in mental fatigue in sport and exercise science research, the impact of mental fatigue on performance decline is growing in evidence. The following section will outline the current research to investigate the impact of mental fatigue on performance in team and individual sports.

Basketball

In a recent study, 32 junior Brazilian State Championship level basketball players competed in small-sided-games following exposure to either a 30-min incongruent Stroop task or control condition (sitting quietly in front of the computer screen completing a simple task for 10-min, immediately followed by relaxing in the room for a further 20-min) (Moreira et al., 2018). Salivary testosterone, cortisol, and alpha-amylase responses were measured pre Stroop/control condition and technical performance was analysed throughout the small sided games. A large increase was reported in pre-control treatment to post-small sided games for salivary testosterone and alpha-amylase, along with a small difference from pre-Stroop-task to post-SSG in salivary cortisol and a moderate difference for alpha-amylase. Small changes in cortisol for both conditions were observed. Regarding technical performance, significantly greater number of turnovers was observed in the small sided games from the Stroop condition.

Handball

Research has shown that mental fatigue impairs physical performance without affecting physiological markers of fatigue (Penna, Campos, Pires et al., 2018). Twelve recreational handball players completed a YoYo IR1 test on two occasions separated by at least 72 hours, preceded by a mental fatigue (30-min Stroop Colour-Word Test) or control (30 minute emotionally neutral video) condition. Significantly higher ratings of mental fatigue and mental effort were reported following the Stroop Test condition. Running performance was only impaired in mental fatigue condition (with a significantly higher RPE compared to the control condition), however no differences in heart rate recovery and blood lactate levels were reported across conditions. These results show that exposure to cognitively demanding tasks before sport-specific action increases perception of effort without increasing physiological variables.

Cricket

To date, there is one study that has assessed the effects of mental fatigue on cricket related performance (Veness et al., 2017). Ten elite cricket players performed a cricket specific sprinting test (run-two test) which simulates running between wickets with a bat in hand, a Batak Lite reaction test and a Yo-Yo Intermittent Recovery Level 1 (Yo-Yo IR1) test after completing either a 30-min control condition or a 30-min Stroop task. Compared to the control task (reading magazines), run-two test performance and Yo-Yo IR1 distance were significantly lower in the mental fatigue condition. The time scale to complete the battery of tests in this study is likely to be considerably shorter than the duration of a cricket match, meaning additional research is warranted to explore the effects of mental fatigue on real match performance.

Table tennis

The impact of mental fatigue on table tennis performance is also limited to one study (Le Mansec et al., 2017). French regional – national level table tennis players (n=22) completed a table tennis specific performance task (performing 45 forehand strokes, hitting three alternate targets positioned in central and left/right sided locations) following completion of four different protocols. These were an eccentric elbow flexor exercise (biceps fatigue), an eccentric knee extensor exercise (quadriceps fatigue) a mentally fatiguing trial (90-min AX-CPT) and a control condition (watching a movie for 90-min). Only the biceps fatigue and mental fatigue conditions induced a decrease in accuracy in the performance task. This decrease in accuracy is likely explained by an increased ball speed in the biceps fatigue condition, and a decreased ball speed in the mental fatigue condition.

Table 4 – Mental fatigue in sport

Study	Subjects	Study design	Mentally fatiguing task	Measure	Exercise	Results
Moreira et al., (2018)	32 male state championship basketball players	Randomised crossover	30-min Stroop	s-RPE	10-min SSG	↑ Hormonal response ↓ Technical performance
Penna et al., (2018)	12 recreational handball players	Randomised crossover	30-min Stroop	VAS	YoYo IR1	↓ YoYo IR1 performance ↑RPE No difference in HR or BLa
Veness et al., (2017)	10 elite cricket players	Randomised crossover	30-min Stroop	VAS	YoYo IR1 Run-two test Batak Lite reaction test	↓ YoYo IR1 & run-two test performance
LeMansec et al., (2017)	22 regional – national level table tennis players	Randomised crossover	90-min AX-CPT	VAS	Table tennis-specific performance task	↓ Technical performance

2.9 - Summary

There is overwhelming evidence in isolated task performance conditions that exposure to cognitive activity before sport-specific activity will decreases several aspects of performance at recreational competition level. Several studies have demonstrated that induced mental fatigue (30-min modified Stroop task) impairs sport-specific physical performance (Penna et al., 2018; Veness et al., 2017), technical performance (Moreira et al., 2018; LeMansec et al., 2017) and hormonal response (Moreira et al., 2018). However, these findings should be approached with caution. For example, the sport-specific performance tests are shortened and isolated aspects of full completion, meaning the impact of mental fatigue on competition performance (i.e. full match-play) remains unknown.

Furthermore, the participants in each of the studies do not compete at an elite level, and the modified Stroop task unlikely reflects the real-life cognitive demands of elite athletes. Therefore, future research in sport must consider the use of more ecologically valid mentally fatiguing protocols and performance tasks, with the inclusion of elite level athletes.

3 – WHAT IS THE PRESENT IMPACT OF MENTAL FATIGUE ON FOOTBALL-SPECIFIC PERFORMANCE?

3.1 - Rationale

Six investigative studies have investigated the impact of induced mental fatigue on football-specific performance. The following chapter of the thesis aims to examine the current level of evidence for the impact of induced mental fatigue in football.

3.2 - Mental Fatigue and Soccer: Current Knowledge and Future Directions.

This section contains the following published manuscript:

Smith MR, Thompson C, Marcora SM, Skorski S, Meyer T, Coutts AJ. Mental Fatigue and Soccer: Current Knowledge and Future Directions. Sports Medicine. 2018 Apr 5:1-8.

The citations and references of this manuscript are formatted to the requirements of Sports Medicine. These citations only relate to the reference list in this thesis chapter and not to the reference list included at the end of this thesis.

Title/subtitle: Mental Fatigue and Soccer: Current Knowledge and Future Directions

Running Heading: Mental Fatigue and Soccer

Mitchell R. Smith[1], Chris Thompson[2], Samuele M. Marcora[3], Sabrina Skorski[2], Tim Meyer[2] & Aaron J. Coutts[4]

[1]Exercise and Sports Science, Faculty of Science, University of Newcastle, Australia

[2]Institute of Sport and Preventative Medicine, Saarland University, Germany

[3]Endurance Research Group, School of Sport and Exercise Sciences, University of Kent at Medway, United Kingdom.

[4]Sport and Exercise Discipline Group, Faculty of Health, University of Technology Sydney, Australia.

Corresponding Author

Dr Mitchell Smith

Telephone: +612 4033 9235

Email: Mitch.Smith@newcastle.edu.au

Author ORCID

Mitchell Smith: 0000-0002-8168-5405

Sabrina Skorski: 0000-0001-8449-6872

Samuele Marcora: 0000-0002-1570-7936

Aaron Coutts: 0000-0002-1782-7691

Abstract

Fatigue is a complex state with multiple physiological and psychological origins. However, fatigue in soccer has traditionally been investigated from a physiological perspective, with little emphasis on the cognitive demands of competition. These cognitive demands may induce mental fatigue, which could contribute to the fatigue-related performance decrements observed during and after soccer matches. Recent research investigating the relationship between mental fatigue and soccer-specific performance supports this suggestion. This leading article provides an overview of the research in this emerging field, outlining the impact of mental fatigue on soccer-specific physical, technical, decision-making, and tactical performances. The second half of this review provides directions for future research in response to the limitations of the existing research. Particular emphasis is placed on translating the current body of knowledge into practical applications, and developing a greater understanding of the mechanisms underpinning the negative impact of mental fatigue on soccer performance. A conceptual model is presented to help direct this future research.

Key Points

- Mental fatigue impairs multiple aspects of soccer-specific performance.
- Future research should focus on understanding the mechanisms underlying performance impairments, and applying these findings within the performance environment.
- Soccer clubs should consider strategies to avoid and/or attenuate the negative effects of mental fatigue on soccer performance.

Compliance with Ethical Standards

Mitchell R. Smith, Chris Thompson, Samuele M. Marcora, Sabrina Skorski, Tim Meyer and Aaron J. Coutts declare that they have no conflict of interest.

No funding was provided for completion of this manuscript.

1. INTRODUCTION

Soccer requires prolonged low-intensity activity interspersed with repeated short bouts of high-intensity activity [1]. This physically demanding activity profile causes fatigue, which may reduce distances covered towards the end of a match, and following high-intensity periods of a match [2-4]. This “match-related fatigue” may also reduce the quantity and quality of technical performance towards the end of a match [5].

The perceptual-cognitive demands of soccer competition are also extremely challenging [6]. Indeed, soccer players must remain alert for extended periods, constantly scanning their dynamic performance environment and attending only to relevant information. Players must then integrate this information with tactical strategies, and opposition and teammate tendencies (previously stored in memory) to make accurate decisions under strict time constraints [7]. Competing at a high level with potentially congested playing schedules may increase these psychological demands [8]. Therefore, players likely experience mental fatigue during competition, which may contribute to the performance reductions observed towards the end of a match.

Mental fatigue is a psychobiological state, characterised by feelings of tiredness and a lack of energy, and induced by prolonged periods of demanding cognitive activity [9, 10]. The negative impact of mental fatigue on endurance performance is well-established, and has been attributed to increased perception of effort (for review see [11]). Comprehensive evidence also demonstrates that mental fatigue impairs cognitive [9, 12] and skilled motor [13, 14] performances. These impairments have been attributed to altered attentional focus [9], reduced performance monitoring/adjustment [10], slower and less accurate reactions [12], and poor use of visual cues for action preparation [12, 15]. Therefore, as these executive functions are important for sport-specific performance, researchers have recently begun investigating the effects of mental fatigue on soccer performance [16-20].

This review summarises the recent literature on mental fatigue and soccer performance, and provides direction for future research in this emerging field. The paper is structured in two sections: (i) a review of existing literature, outlining the impact of acute mental fatigue on various factors associated with successful soccer performance; and (ii) suggested avenues for future research, based on the limitations of the existing literature. This second section emphasises the practical application of this research, and provides a conceptual mechanistic model to direct future research.

2. CURRENT KNOWLEDGE

2.1. Physical Performance

Time-motion analysis investigations have revealed reductions in physical activity as matches progress [2-4]. Most existing research attributes these changes to cardiorespiratory, metabolic, and neuromuscular mechanisms of fatigue (physical fatigue) [1]. However, our understanding of fatigue in soccer is broadening, acknowledging the significant psychological stress of competition, and its impact on performance [8, 21]. Therefore, several recent investigations have assessed the impact of mental fatigue on soccer-specific physical performance [16-18, 22].

Using a non-motorised treadmill protocol simulating the activity profile of team sport gameplay, Smith et al., [22] demonstrated that mental fatigue impairs intermittent running performance. In this investigation, 10 team sport athletes performed a 45-min intermittent running protocol following a 90-min cognitively demanding computer task (mental fatigue) and a control treatment (documentary). Mental fatigue reduced running velocities at low intensities, while high-intensity and peak sprint velocities remained similar between conditions. These observed impairments to performance were attributed to higher perception of effort in the mentally fatigued condition, rather than physiological differences [22].

A subsequent study was conducted to verify these initial findings using the Yo-Yo Intermittent Recovery Test, Level 1 (Yo-Yo IR1); a validated protocol, correlated to match running profiles [23], and more familiar to soccer players [18]. Results of this study confirmed previous findings, as all 12 recreational soccer players ran shorter distances in the Yo-Yo IR1 following a 30-min mentally fatiguing Stroop task, compared to an emotionally neutral control. In line with previous investigations [22, 24, 25], this reduction in running performance in mentally fatigued players was mediated by an increased perception of effort.

In contrast to laboratory-controlled conditions, mental fatigue has an unclear influence on soccer-specific physical performance in applied settings [16, 17, 26]. Badin et al., [16], and Coutinho et al., [17] investigated the effects of mental fatigue on performance during 5 vs 5, and 6 vs 6 (plus goalkeeper) small-sided games (SSG), respectively, with only one mentally fatigued team per SSG. Coutinho et al., [26] mentally fatigued both teams before 5 vs 5 (plus goalkeeper) SSG, and compared performance to a control vs control SSG. Perception of effort during the SSG was likely higher in mentally fatigued players in Badin et al., [16], and Coutinho et al., [17] , however, players' physical activity profiles, assessed using global positioning systems, were not clearly different between conditions. [16, 17]. Indeed, differences in most physical performance variables (distances covered, accelerations and decelerations) were either unclear or trivial., Coutinho et al., [26] did not assess RPE during the SSG but reported a likely small reduction in total distance (possibly small reductions in moderate- and high-intensity ratios; likely trivial differences in low-intensity ratio) in mentally fatigued players. Therefore, it is possible, but unclear whether mental fatigue influences soccer-specific physical performance in applied settings, and is likely to depend on the fatigue status of the opposition. The contrast in findings between laboratory-based (clear impairment) and applied settings (unclear influence) is likely due to the open nature of SSG, which involve technical skills, tactical considerations, decision-making, and competition against an opposing team [27]. During SSG, these factors likely dictate player movement patterns to a greater extent than perception of effort.

2.2. Technical Performance

Although physical activity profiles are important in soccer, technical skill performance generally determines match success [28]. Some [5, 28], but not all [2] research indicates that performance of technical skills declines over the course of a match. Again, these changes are typically associated with physical fatigue [5]. However, recent research demonstrates that mental fatigue impairs performance of fundamental motor skills (manual dexterity, anticipation timing, and goal-directed arm movements) [13, 29]. Additional evidence suggests that these mental-fatigue related impairments to fundamental motor skills transfer to soccer-specific skills [16, 18, 20].

Recent studies have investigated the impact of mental fatigue on technical performance in both controlled and applied settings. Following a 30-min Stroop task, 14 well-trained players performed less accurate passes, and slower, less accurate shots on goal in the Loughborough Soccer Passing (LSPT) and Shooting Tests (LSST) [18, 20]. No between-condition differences existed for players' movement speed during the tests, suggesting that a possible speed-accuracy trade-off exists. Similar reductions in LSPT performance have previously been observed following a soccer match [5], indicating that mental fatigue may contribute to performance decrements during competition. However, results from the LSPT must be interpreted with care, as recent research suggests that this test has impractical criterion validity in elite youth soccer players [30]. Nevertheless research assessing the impact of mental fatigue on soccer skills during SSG supports the hypothesis that mental fatigue contributes to technical impairments during match play [16]. Indeed, mental fatigue reduced players' passing accuracy during the SSG. Additionally, mentally fatigued players had a lower percentage of positive involvements and possessions, less successful tackles, and more ball control errors. Taken collectively, these findings show that mental fatigue impairs several offensive and defensive soccer-specific technical skills and may be partially responsible for reductions observed during competition [5, 28].

2.3. Decision-making and Tactical Performance

Soccer players' capability to quickly identify and interpret relevant cues and formulate an appropriate response is critical for successful performance [31-33]. Players utilise these perceptual-cognitive skills to decide on appropriate technical involvements, and movements based on the positioning of other players and the ball (tactical behaviour). Indeed, players with superior perceptual-cognitive skills are typically better decision-makers [34] and play at a higher competitive level [33]. Previous research has shown that mental fatigue impairs perceptual-cognitive performance during computer-based tasks [9, 10, 12, 15]. Therefore, researchers have recently investigated whether mental fatigue also affects soccer-specific perceptual-cognitive performance [17, 19].

Preliminary findings suggest that mental fatigue impairs perceptual-cognitive performance of soccer players [17, 19]. Smith et al., [19] studied 12 well-trained soccer players as they performed a film-based soccer-specific decision-making task [33, 34] following a 30-min Stroop task or control treatment. Mental fatigue impaired both speed and accuracy of soccer-specific decisions, but had minimal impact on visual search behaviour [19]. The aforementioned investigations by Coutinho et al., [17] and Coutinho et al., [26] (see section 2.1. Physical Performance) also assessed the impact of mental fatigue on tactical performance in SSG. When mentally fatigued, players in Coutinho et al., [17] possibly spent less time synchronised in the lateral direction. Mental fatigue also possibly reduced the speed of team dispersion and very likely reduced the speed of team contraction. Mentally fatigued players in Coutinho et al., [26] likely spent less time synchronised in the longitudinal direction, possibly increased the regularity in distance between player dyads, and possibly decreased team dispersion. The differences between these findings are again likely a result of the fatigue status of the opposition (fatigue vs control, or fatigue vs fatigue).

In summary, the existing literature demonstrates that mental fatigue impairs soccer-specific physical, technical, and perceptual-cognitive performances. However, additional research is required to confirm whether these impairments, observed mainly in controlled settings, translate into performance reductions during competition. The following section of this review expands on this need, and outlines additional avenues for future research.

3. FUTURE DIRECTIONS

The investigations reviewed above provide preliminary evidence that mental fatigue impairs soccer performance. However, there are two clear lines of additional research required to assist coaching staff and players in managing mental fatigue. Firstly, researchers should aim to integrate theory and practice, studying mental fatigue and soccer performance with an applied approach. Secondly, future investigations should attempt to clarify the mechanisms behind the observed influence of mental fatigue on soccer-specific performance. Several suggestions for this future research are provided below.

3.1. Applied Research

The reductions in performance observed due to mental fatigue appear to align with changes that have been attributed to match-related fatigue [2-5]. However, there is no empirical evidence that soccer players experience mental fatigue during competition. Mashiko et al., [35] used the Profile of Mood State (POMS) questionnaire to assess mood before and after rugby union matches, reporting an increase in mental fatigue. However, as the fatigue subscale of the POMS does not differentiate mental and physical fatigue [36], it is difficult to determine whether the increased fatigue was due to mental or physical exertion, or a combination. Additionally, no such investigations exist in soccer players. Therefore, future investigations should directly assess mental fatigue pre- and post-game using as many subjective (specific to mental fatigue), and objective (electroencephalography [37], electrooculography [38], reaction time and accuracy [39]) assessment tools as practically possible. These investigations should ideally collect data from several games across a season, as factors such as winning/losing, quality of opposition, fixture congestion, and stage of season are likely to impact at least subjective assessments [40]. This research should also consider the positive impact of exercise on arousal and cognitive performance, which may influence results [41].

Another limitation of the existing research is the use of prolonged computer or paper-based cognitive tasks (e.g. Stroop) to induce mental fatigue. Although the cognitive demands of these tasks (i.e. sustained attention and inhibitory control) are also present during soccer competition, players do not perform these tasks prior to taking the field. Coutinho et al., [17] partially addressed this limitation, inducing mental fatigue with a motor task. Players performed a series of agility ladder drills for 20 min, while juggling a tennis ball to increase attentional demands. This novel motor task is an improvement on computer-based tasks, but is also an atypical pre-match activity for soccer players. However, it is possible that some pre-match activities/routines (e.g. prolonged tactical sessions, player interviews, or playing video games) do induce mental fatigue. Indeed, activities requiring sustained vigilance [9, 42] and/or emotional regulation [43] can induce mental fatigue, and impair subsequent performance. The timing of mentally fatiguing tasks is also critical, as periods of rest can reduce mental fatigue [44]. While players typically rest immediately prior to a match, most existing investigations do not incorporate a break between mentally fatiguing tasks and performance tests. Therefore, future research should investigate whether common pre-match activities induce mental fatigue and assess their impact on performance (after realistic periods of rest). Where this approach is not possible, researchers should induce mental fatigue using 'soccer-specific' tasks like Coutinho et al., [17], rather than computer or paper-based tasks.

Although recent investigations have attempted to utilise more applied environments (i.e. SSG) [16, 17], assessing the impact of mental fatigue on performance during a 90-min match (and extra time where possible) would advance our current knowledge. Indeed, Badin et al., [16] suggested that in their investigation the short duration of the SSG may explain why mental fatigue had no impact on physical performance. It is possible that if participants played a full-length match, perception of effort would have increased further, decreasing the physical activity profile of mentally fatigued players. Due to the likely impairments, researchers should not attempt to mentally fatigue players before competitive matches. Rather, future investigations should assess the impact of mental fatigue on performance during full-length practice matches.

It remains unclear whether mental fatigue impairs soccer performance of elite players. Indeed, the existing literature has investigated well-trained or recreational soccer players. The pressure of elite-level competition likely places greater cognitive demands on elite players as they regulate emotions prior to a match [8]. These demands may induce mental fatigue in elite players during competition. However, recent evidence indicates that professional cyclists are more resistant to mental fatigue than lower-level cyclists [45]. The authors attribute this resistance to the athletes' familiarity with highly demanding cognitive activity during training and competition. Considering the demands of elite soccer training and competition, it is likely that soccer players share this resistance. Nevertheless, research should assess whether soccer-specific cognitively demanding activity induces mental fatigue and/or impairs performance in an elite population. This research may have additional implications for planning training and recovery schedules in an attempt to increase the cognitive demand (e.g. using SSG rather than general or semi-specific physical training) and allow for appropriate recovery from physiological and psychological stresses.

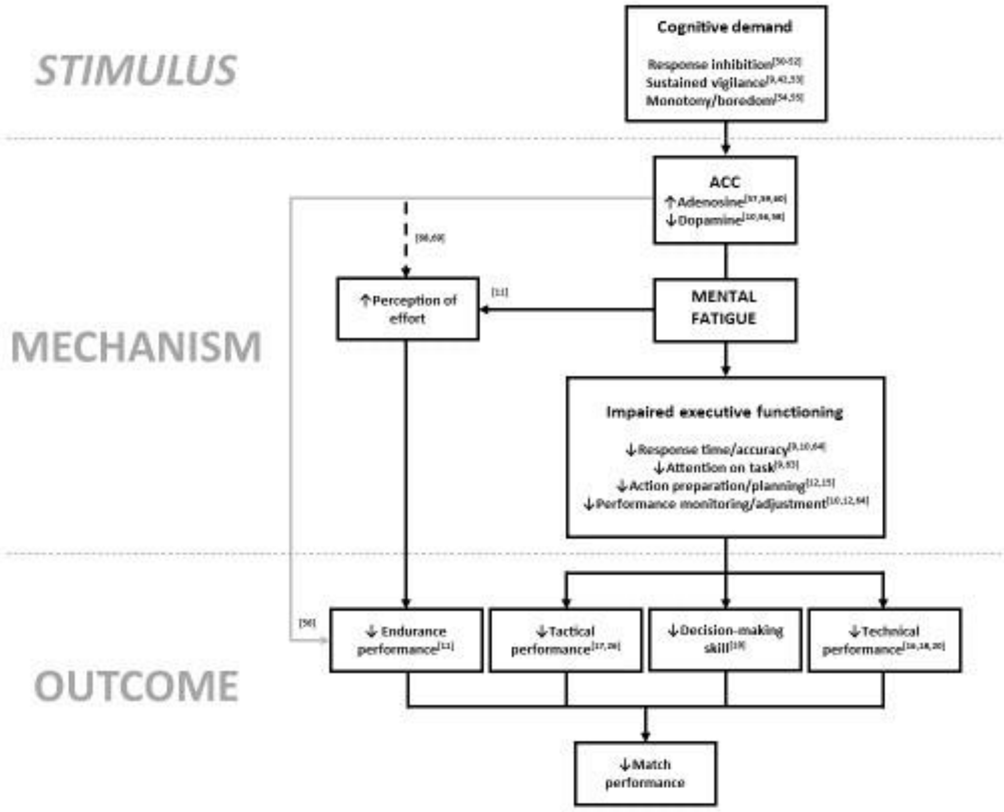
The findings of Martin et al., [45] also warrant investigations into the efficacy of intentionally training under conditions of mental fatigue to increase resistance and improve performance. Indeed, preliminary evidence suggests that systematically training under conditions of mental fatigue reduces perception of effort and improves endurance exercise performance [46]. Future research should examine whether this novel training strategy enhances soccer-specific performance. If so, additional research will be required to identify the most practical and effective prescription guidelines (e.g. optimal timing, volume, frequency, and format of mentally fatiguing activity).

Finally, in elite players, mental fatigue may interact with sleep restriction/deprivation and/or congested schedules to influence performance. For example, research has shown that sleepiness and mental fatigue may work synergistically to impair cognitive performance [44]. This may be important for elite soccer players, as the physical and psychological demands of training and competition can reduce the quality and quantity of athletes' sleep, which may affect subsequent performance [47]. Additionally, although congested fixtures appear to have minimal influence on physical performance, injury rates seem to increase during these periods [48]. It is possible that mental fatigue contributes to this increase in injury rates during congested periods. Indeed, many of the mechanisms proposed to impair skilled performance under conditions of mental fatigue (see below) have been linked to increased injury risk in a laboratory-based slipping task [49]. Therefore, future research should examine the interactive influence of mental fatigue, sleep restriction, and fixture congestion on soccer performance and injury incidence/susceptibility.

3.2. Mechanisms

The mechanisms of fatigue in soccer are complex, with multiple physiological and psychological processes contributing to performance declines [31, 48]. Understanding these mechanisms may assist in the development of novel interventions to attenuate performance impairments. The current research on mental fatigue and soccer performance provides little information regarding the mechanisms responsible for the observed impairments. Nevertheless, fundamental investigations on mental fatigue provide insight into certain mechanisms that appear to align with the results of soccer-specific research. Based on this information, we propose a conceptual mechanistic model (Figure 1) for the impact of mental fatigue on soccer performance. This model was not designed to comprehensively analyse the multifactorial genesis of fatigue, as there are undoubtedly additional mechanisms involved in this complex process. Rather, it outlines one (of many) mechanistic pathway that likely contributes to fatigue-related impairments in soccer. Therefore, this model acts as a tool to direct future research into the mechanisms of mental fatigue in soccer.

Fig. 1 Conceptual model outlining a potential mechanistic pathway for the impact of mental fatigue on soccer performance. ACC anterior cingulate cortex. The gray line indicates evidence from animal research, and the broken line indicates proposed mechanism lacking empirical evidence.



As seen in Figure 1, cognitively demanding tasks requiring response inhibition [50-52], sustained vigilance [9, 42, 53], and monotony [54, 55] induce mental fatigue. These tasks activate the anterior cingulate cortex (ACC), likely leading to elevated adenosine, and a corresponding decrease of dopamine in this brain region [10, 56-61]. The ACC plays a critical role in many executive functions, including effort-based decision-making [62], attentional allocation [9, 63], action preparation [12, 15], and performance monitoring/adjustment [10, 12, 64]. Impairments to these functions may be responsible for the observed decrements in soccer-specific tactical, decision-making, and technical performance [16-20]. However, future investigations should directly assess the accuracy of these proposed mechanisms. For example, utilising dual-task procedures and players of varying skill level may clarify whether attentional changes are responsible for the observed reductions in technical performance. Indeed, highly skilled players require less attentional resources to perform well-learned motor skills [65]. Therefore, if mental fatigue reduces the allocation of attention to task demands, highly skilled players may maintain a higher standard of performance than their lesser skilled counterparts when a secondary task is added.

Previous research demonstrates that mental fatigue increases perception of effort, subsequently reducing endurance performance [11, 24, 25, 66, 67]. However, the mechanisms underlying these observed increases in perception of effort are not clear. Similar to impairments in technical and decision-making performance, altered adenosine/dopamine concentrations in the ACC may be responsible [68, 69]. This suggestion is based on the following theory: (i) the ACC contributes to effort-based decision-making [70, 71]; (ii) mentally fatiguing tasks (e.g. Stroop) activate the ACC, increasing extracellular adenosine [50, 52, 60, 72]; (iii) animal studies show that elevated concentrations of adenosine in the brain impair endurance performance [57]; and (iv) the ergogenic effect of caffeine on endurance performance has been attributed to its role as an adenosine antagonist [57]. Although this proposed mechanism is plausible, further studies in both animals and humans should directly examine the role of adenosine/dopamine interactions in the ACC (and other neurological mechanisms) in regulating perception of effort and endurance performance. More specific directions for future research in this area have been discussed in a previous review [11].

Understanding the mechanisms of mental fatigue will allow for the implementation of tailored interventions to attenuate its negative effect on soccer performance. According to our proposed model (Figure 1), interventions altering adenosine/dopamine levels, actions and interactions may be particularly effective. As stated above, caffeine counteracts mental fatigue [73], at least in part, by blocking adenosine receptors in the brain [57]. This mechanism appears to underpin caffeine's cognitive and physical performance benefits [74, 75]. Indeed, caffeine consumption reverses the negative impact of mental fatigue on physical performance [76], and improves soccer-specific physical and technical performance [77-79]. Therefore, caffeine and mental fatigue have contrasting effects on soccer-specific performance, potentially due to their opposing impact on adenosine/dopamine concentrations. However, additional research is required to assess the interaction between mental fatigue, caffeine consumption, and soccer performance.

4. CONCLUSIONS

The recent literature indicates that mental fatigue may contribute to performance decrements associated with 'match-related fatigue' in soccer. Indeed, induced mental fatigue impairs soccer-specific physical, technical, decision-making, and tactical performance. These findings provide initial experimental evidence, and confirm anecdotal reports of the influence of mental fatigue on soccer performance. However, this remains an emerging field of research, requiring additional investigation. The primary limitation of the existing literature is a lack of direct application to the performance environment. Therefore, future investigations must aim to reconcile research and practice by studying mental fatigue and soccer performance with an applied focus. A deeper understanding of the mechanisms that underpin the negative impact of mental fatigue on soccer performance may assist in directing this future research. A conceptual mechanistic model has been presented for this purpose.

Although further research is required in this emerging field, the existing literature provides adequate evidence that soccer clubs should consider strategies to avoid and/or attenuate the negative effects of mental fatigue on soccer performance.

REFERENCES

1. Mohr M, Krustrup P, Bangsbo J. Fatigue in soccer: a brief review. J Sports Sci. 2005;23(6):593-9.

2. Carling C, Dupont G. Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play? J Sports Sci. 2011;29(1):63-71.

3. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. J Sports Sci. 2003;21(7):519-28.

4. Rampinini E, Coutts AJ, Castagna C, Sassi R, Impellizzeri FM. Variation in top level soccer match performance. Int J Sports Med. 2007;28(12):1018-24.

5. Rampinini E, Impellizzeri FM, Castagna C, Azzalin A, Bravo DF, Wisloff U. Effect of match-related fatigue on short-passing ability in young soccer players. Med Sci Sports Exerc. 2008;40(5):934-42.

6. Walsh V. Is sport the brain's biggest challenge? Curr Biol. 2014;24(18):R859-R60.

7. Nédélec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. Recovery in soccer: Part I-Post-match fatigue and time course of recovery. Sports Med. 2012;42(12):997-1015.

8. Coutts AJ. Fatigue in football: it's not a brainless task! J Sports Sci. 2016;34(14):1296.

9. Boksem MAS, Meijman TF, Lorist MM. Effects of mental fatigue on attention: an ERP study. Cognitive Brain Research. 2005;25(1):107-16. doi:https://doi.org/10.1016/j.cogbrainres.2005.04.011.

10. Lorist M, Boksem MAS, Ridderinkhof KR. Impaired cognitive control and reduced cingulate activity during mental fatigue. Cognitive Brain Research. 2005;24(2):199-205. doi:https://doi.org/10.1016/j.cogbrainres.2005.01.018.

11. Van Cutsem J, Marcora S, De Pauw K, Bailey S, Meeusen R, Roelands B. The Effects of Mental Fatigue on Physical Performance: A Systematic Review. Sports Med. 2017:1-20.

12. Boksem MAS, Meijman TF, Lorist MM. Mental fatigue, motivation and action monitoring. Biol Psychol. 2006;72(2):123-32. doi:https://doi.org/10.1016/j.biopsycho.2005.08.007.

13. Duncan MJ, Fowler N, George O, Joyce S, Hankey J. Mental fatigue negatively influences manual dexterity and anticipation timing but not repeated high-intensity exercise performance in trained adults. Res Sports Med. 2015;23(1):1-13.

14. Lal SKL, Craig A. A critical review of the psychophysiology of driver fatigue. Biol Psychol. 2001;55(3):173-94. doi:http://dx.doi.org/10.1016/S0301-0511(00)00085-5.

15. Lorist M, Klein M, Nieuwenhuis S, Jong R, Mulder G, Meijman TF. Mental fatigue and task control: planning and preparation. Psychophysiology. 2000;37(5):614-25.

16. Badin OO, Smith MR, Conte D, Coutts AJ. Mental fatigue impairs technical performance in small-sided soccer games. Int J Sports Physiol Perform. 2016;In press. doi:http://dx.doi.org/10.1123/ijspp.2015-0710.

17. Coutinho D, Gonçalves B, Travassos B, Wong DP, Coutts AJ, Sampaio JE. Mental Fatigue and Spatial References Impair Soccer Players' Physical and Tactical Performances. Front Psychol. 2017;8(1645). doi:10.3389/fpsyg.2017.01645.

18. Smith MR, Coutts AJ, Merlini M, Deprez D, Lenoir M, Marcora SM. Mental fatigue impairs soccer-specific physical and technical performance. Med Sci Sports Exerc. 2016;48(2):267-76. doi:https://doi.org/10.1249/MSS.0000000000000762.

19. Smith MR, Zeuwts L, Lenoir M, Hens N, De Jong LMS, Coutts AJ. Mental fatigue impairs soccer-specific decision-making skill. J Sports Sci. 2016;In press:1-8. doi:10.1080/02640414.2016.1156241.

20. Smith MR, Fransen J, Deprez D, Lenoir M, Coutts AJ. Impact of mental fatigue on speed and accuracy components of soccer-specific skills. Science and Medicine in Football. 2017;1(1):48-52. doi:10.1080/02640414.2016.1252850.

21. Paul DJ, Bradley PS, Nassis GP. Factors affecting match running performance of elite soccer players: Shedding some light on the complexity. Int J Sports Physiol Perform. 2015;10(4):516-9.

22. Smith MR, Marcora SM, Coutts AJ. Mental fatigue impairs intermittent running performance. Med Sci Sports Exerc. 2015;47(8):1682-90.

23. Castagna C, Impellizzeri F, Cecchini E, Rampinini E, Alvarez JCB. Effects of intermittent-endurance fitness on match performance in young male soccer players. J Strength Cond Res. 2009;23(7):1954-9.

24. Brownsberger J, Edwards A, Crowther R, Cottrell D. Impact of mental fatigue on self-paced exercise. Int J Sports Med. 2013;34(12):1029-36.

25. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. J Appl Physiol. 2009;106(3):857-64. doi:10.1152/japplphysiol.91324.2008.

26. Coutinho D, Gonçalves B, Wong DP, Travassos B, Coutts AJ, Sampaio J. Exploring the effects of mental and muscular fatigue in soccer players' performance. Human Movement Science. in press:1-10.

27. Hill-Haas SV, Dawson B, Impellizzeri FM, Coutts AJ. Physiology of small-sided games training in football. Sports Med. 2011;41(3):199-220.

28. Rampinini E, Impellizzeri FM, Castagna C, Coutts AJ, Wisloff U. Technical performance during soccer matches of the Italian Serie A league: Effect of fatigue and competitive level. J Sci Med Sport. 2009;12(1):227-33.

29. Rozand V, Lebon F, Papaxanthis C, Lepers R. Effect of mental fatigue on speed-accuracy trade-off. Neuroscience. 2015;297:219-30.

30. Serpiello FR, Cox A, Oppici L, Hopkins WG, Varley MC. The Loughborough Soccer Passing Test has impractical criterion validity in elite youth football. Science and Medicine in Football. 2017;1(1):60-4. doi:10.1080/02640414.2016.1254810.

31. Knicker AJ, Renshaw I, Oldham ARH, Cairns SP. Interactive processes link the multiple systems of fatigue in sport competition. Sports Med. 2011;41(4):307-28.

32. Travassos B, Gonçalves B, Marcelino R, Monteiro R, Sampaio J. How perceiving additional targets modifies teams' tactical behavior during football small-sided games. Human Movement Science. 2014;38:241-50. doi:https://doi.org/10.1016/j.humov.2014.10.005.

33. Vaeyens R, Lenoir M, Williams AM, Mazyn L, Philippaerts RM. The effects of task constraints on visual search behavior and decision-making skill in youth soccer players. Journal of Sport and Exercise Psychology. 2007;29(2):147.

34. Vaeyens R, Lenoir M, Williams AM, Philippaerts RM. Mechanisms underpinning successful decision making in skilled youth soccer players: An analysis of visual search behaviors. Journal of Motor Behavior. 2007;39(5):395-408.

35. Mashiko T, Umeda T, Nakaji S, Sugawara K. Position related analysis of the appearance of and relationship between post-match physical and mental fatigue in university rugby football players. Br J Sports Med. 2004;38(5):617-21.

36. Terry PC, Lane AM, Fogarty GJ. Construct validity of the Profile of Mood States-Adolescents for use with adults. Psychol Sport Exerc. 2003;4(2):125-39. doi:https://doi.org/10.1016/S1469-0292(01)00035-8.

37. Balasubramanian V, Adalarasu K, Gupta A. EEG based analysis of cognitive fatigue during simulated driving. International Journal of Industrial and Systems Engineering. 2011;7(2):135-49. doi:https://doi.org/10.1504/IJISE.2011.038563.

38. Craig A, Tran Y, Wijesuriya N, Nguyen H. Regional brain wave activity changes associated with fatigue. Psychophysiology. 2012;49(4):574-82. doi:10.1111/j.1469-8986.2011.01329.x.

39. Lamond N, Dawson D, Roach GD. Fatigue assessment in the field: validation of a hand-held electronic psychomotor vigilance task. Aviation, Space, and Environmental Medicine. 2005;76(5):486-9.

40. Brito J, Hertzog M, Nassis GP. Do match-related contextual variables influence training load in highly trained soccer players? The Journal of Strength & Conditioning Research. 2016;30(2):393-9.

41. Lambourne K, Tomporowski P. The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. Brain Res. 2010;1341(1):12-24.

42. Van Dongen H, Belenky G, Krueger JM. Investigating the temporal dynamics and underlying mechanisms of cognitive fatigue. In: Ackerman PL, editor. Cognitive Fatigue: Multidisciplinary Perspectives on Current Research and Future Applications. Washington, DC: American Psychological Association; 2011. p. 127-47.

43. Wagstaff C. Emotion regulation and sport performance. Journal of Sport and Exercise Psychology. 2014;36(4):401-12.

44. Balkin TJ, Wesensten NJ. Differentiation of sleepiness and mental fatigue effects. In: Ackerman PL, editor. Cognitive Fatigue: Multidisciplinary Perspectives on Current Research and Future Applications. Washington, DC: American Psychological Association; 2011. p. 47-66.

45. Martin K, Staiano W, Menaspà P, Hennessey T, Marcora S, Keegan R et al., Superior Inhibitory Control and Resistance to Mental Fatigue in Professional Road Cyclists. PLoS One. 2016;11(7):e0159907.

46. Marcora SM, Staiano W, Merlini M. A randomized controlled trial of brain endurance training (bet) to reduce fatigue during endurance exercise. Med Sci Sports Exerc. 2015;47(5S):198.

47. Fullagar HHK, Skorski S, Duffield R, Hammes D, Coutts AJ, Meyer T. Sleep and Athletic Performance: The Effects of Sleep Loss on Exercise Performance, and Physiological and Cognitive Responses to Exercise. Sports Med. 2015;45(2):161-86. doi:10.1007/s40279-014-0260-0.

48. Silva J, Rumpf M, Hertzog M, Castagna C, Farooq A, Girard O et al., Acute and Residual Soccer Match-Related Fatigue: A Systematic Review and Meta-analysis. Sports Med. 2018;48(3):1-45.

49. Lew FL, Qu X. Effects of mental fatigue on biomechanics of slips. Ergonomics. 2014;57(12):1927-32.

50. Bush G, Whalen PJ, Rosen BR, Jenike MA, McInerney SC, Rauch SL. The counting Stroop: an interference task specialized for functional neuroimaging—validation study with functional MRI. Hum Brain Mapp. 1998;6(4):270-82.

51. MacDonald AW, Cohen JD, Stenger VA, Carter CS. Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. Science. 2000;288(5472):1835-8.

52. Mostofsky SH, Simmonds DJ. Response inhibition and response selection: two sides of the same coin. J Cogn Neurosci. 2008;20(5):751-61. doi:10.1162/jocn.2008.20500.

53. Gunzelmann G, Moore LR, Gluck KA, Van Dongen H, Dinges DF. Fatigue in sustained attention: Generalizing mechanisms for time awake to time on task. In: Ackerman PL, editor. Cognitive Fatigue: Multidisciplinary Perspectives on Current Research and Future Applications. Washington, DC: American Psychological Association; 2011. p. 83-101.

54. Desmond PA, Matthews G. Implications of task-induced fatigue effects for in-vehicle countermeasures to driver fatigue. Accid Anal Prev. 1997;29(4):515-23.

55. Lorist MM, Faber LG. Consideration of the influence of mental fatigue on controlled and automatic cognitive processes and related neuromodulatory effects. In: Ackerman PL, editor. Cognitive Fatigue: Multidisciplinary Perspectives on Current Research and Future Applications. Washington, DC: American Psychological Association; 2011. p. 105-26.

56. Boksem MAS, Tops M. Mental fatigue: Costs and benefits. Brain Research Reviews. 2008;59(1):125-39. doi:https://doi.org/10.1016/j.brainresrev.2008.07.001.

57. Davis JM, Zhao Z, Stock HS, Mehl KA, Buggy J, Hand GA. Central nervous system effects of caffeine and adenosine on fatigue. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology. 2003;284(2):R399-R404.

58. Holroyd CB, Coles MG. The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. Psychol Rev. 2002;109(4):679-708.

59. Lorist M, Tops M. Caffeine, fatigue, and cognition. Brain Cogn. 2003;53(1):82-94.

60. Lovatt D, Xu Q, Liu W, Takano T, Smith NA, Schnermann J et al., Neuronal adenosine release, and not astrocytic ATP release, mediates feedback inhibition of excitatory activity. Proceedings of the National Academy of Sciences. 2012;109(16):6265-70.

61. Salamone JD, Yohn SE, López-Cruz L, San Miguel N, Correa M. Activational and effort-related aspects of motivation: neural mechanisms and implications for psychopathology. Brain. 2016;139(5):1325-47.

62. Walton ME, Kennerley SW, Bannerman DM, Phillips PEM, Rushworth MFS. Weighing up the benefits of work: Behavioral and neural analyses of effort-related decision making. Neural Networks. 2006;19(8):1302-14. doi:http://dx.doi.org/10.1016/j.neunet.2006.03.005.

63. Ackerman PL. 100 years without resting. In: Ackerman PL, editor. Cognitive Fatigue: Multidisciplinary Perspectives on Current Research and Future Applications. Washington, DC: American Psychological Association; 2011. p. 11-43.

64. Kato Y, Endo H, Kizuka T. Mental fatigue and impaired response processes: event-related brain potentials in a Go/NoGo task. Int J Psychophysiol. 2009;72(2):204-11.

65. Smith MD, Chamberlin CJ. Effect of adding cognitively demanding tasks on soccer skill performance. Percept Mot Skills. 1992;75(3):955-61.

66. MacMahon C, Schücker L, Hagemann N, Strauss B. Cognitive fatigue effects on physical performance during running. Journal of Sport and Exercise Psychology. 2014;36(4):375-81.

67. Pageaux B, Marcora SM, Lepers R. Prolonged mental exertion does not alter neuromuscular function of the knee extensors. Med Sci Sports Exerc. 2013;45(12):2254-64. doi:https://doi.org/10.1249/MSS.0b013e31829b504a.

68. Pageaux B, Lepers R, Dietz KC, Marcora SM. Response inhibition impairs subsequent self-paced endurance performance. Eur J Appl Physiol. 2014;114(5):1095-105. doi:10.1007/s00421-014-2838-5.

69. Williamson J, McColl R, Mathews D, Mitchell J, Raven P, Morgan W. Hypnotic manipulation of effort sense during dynamic exercise: cardiovascular responses and brain activation. J Appl Physiol. 2001;90(4):1392-9.

70. Rudebeck PH, Walton ME, Smyth AN, Bannerman DM, Rushworth MF. Separate neural pathways process different decision costs. Nat Neurosci. 2006;9(9):1161-8.

71. Walton ME, Bannerman DM, Alterescu K, Rushworth MF. Functional specialization within medial frontal cortex of the anterior cingulate for evaluating effort-related decisions. J Neurosci. 2003;23(16):6475-9.

72. Swick D, Jovanovic J. Anterior cingulate cortex and the Stroop task: neuropsychological evidence for topographic specificity. Neuropsychologia. 2002;40(8):1240-53.

73. Van Cutsem J, De Pauw K, Marcora S, Meeusen R, Roelands B. A caffeine-maltodextrin mouth rinse counters mental fatigue. Psychopharmacology (Berl). in press:1-12. doi:10.1007/s00213-017-4809-0.

74. Ataka S, Tanaka M, Nozaki S, Mizuma H, Mizuno K, Tahara T et al., Effects of oral administration of caffeine and D-ribose on mental fatigue. Nutrition. 2008;24(3):233-8.

75. Kennedy DO, Scholey AB. A glucose-caffeine 'energy drink'ameliorates subjective and performance deficits during prolonged cognitive demand. Appetite. 2004;42(3):331-3.

76. Azevedo R, Silva-Cavalcante MD, Gualano B, Lima-Silva AE, Bertuzzi R. Effects of caffeine ingestion on endurance performance in mentally fatigued individuals. Eur J Appl Physiol. 2016;116(11):2293-303. doi:10.1007/s00421-016-3483-y.

77. Del Coso J, Muñoz-Fernández VE, Muñoz G, Fernández-Elías VE, Ortega JF, Hamouti N et al., Effects of a caffeine-containing energy drink on simulated soccer performance. PLoS One. 2012;7(2):e31380.

78. Foskett A, Ali A, Gant N. Caffeine enhances cognitive function and skill performance during simulated soccer activity. Int J Sport Nutr Exerc Metab. 2009;19(4):410-23.

79. Lara B, Gonzalez-Millán C, Salinero JJ, Abian-Vicen J, Areces F, Barbero-Alvarez JC et al., Caffeine-containing energy drink improves physical performance in female soccer players. Amino Acids. 2014;46(5):1385-92.

4 – WHAT ARE THE LIMITATIONS OF THE CURRENT MENTAL FATIGUE IN FOOTBALL LITERATURE?

4.1 – Rationale

The literature review in chapter 3 concluded that induced mental fatigue has negatively influenced football specific physical, technical, tactical and decision making performance in six original investigative studies (Coutinho et al., 2018; Coutinho et al., 2017; Smith et al., 2017; Badin, Smith, Conte, & Coutts 2016; Smith et al., 2016a; Smith et al., 2016b). Limitations of the research were also briefly discussed yet warrants further investigation in order to strengthen future study designs. Therefore, the purpose the following study was to critically examine the methodology of the current mental fatigue in football literature, with a focus on the current methods of inducing mental fatigue, measuring mental fatigue and the playing standard of the participants recruited.

4.2 - Mental fatigue in football: is it time to shift the goalposts?

This section contains the following published manuscript:

Thompson, C. J., Fransen, J., Skorski, S., Smith, M. R., Meyer, T., Barrett, S., & Coutts, A. J. (2018). Mental fatigue in football: Is it time to shift the goalposts? An evaluation of the current methodology. *Sports Medicine*, *49*(2), 177-183.

The citations and references of this manuscript are formatted to the requirements of Sports Medicine. These citations only relate to the reference list in this thesis chapter and not to the reference list included at the end of this thesis.

Title/subtitle: Mental fatigue in football: is it time to shift the goalposts?

Running Heading: Mental Fatigue and Football

Chris J Thompson[1], Job Fransen[2], Sabrina Skorski[1], Mitchell R Smith[3], Tim Meyer[1], Steve Barrett[4], Aaron J Coutts[2].

1 - Institute of Sport and Preventive Medicine, Saarland University, Saarbrücken, Germany.

2 - Sport and Exercise Discipline Group, Faculty of Health, University of Technology Sydney, Moore Park, Australia.

3 - Exercise and Sports Science, Faculty of Science, University of Newcastle, Ourimbah, Australia.

4 - Sports Medicine and Science Department, Hull City FC, Kingston Upon Hull, UK.

Corresponding author

Chris Thompson

Telephone - +49 (0) 681 302 70413

Email - chris.thompson@uni.saarland.de

Author ORCID

Chris Thompson: 0000-0001-5333-3616

Job Fransen: 0000-0003-3355-1848

Sabrina Skorski: 0000-0001-8449-6872

Mitchell Smith: 0000-0002-8168-5405

Steve Barrett: 0000-0002-6751-9937

Aaron Coutts: 0000-0002-1782-7691

ABSTRACT

Research in football for a long time has focused on the physical nature of fatigue as opposed to its mental aspects. However since 2016, six original articles have investigated the effects of induced mental fatigue in football on isolated physical, skill and decision making performance tests, along with physical, technical and tactical performance outcomes in small-sided-games. Whilst these studies have overall shown a negative impact of mental fatigue on task performance, this current opinion aims to critically examine the methodological approach to this problem, most notably the lack of ecological validity when inducing mental fatigue and the present approach to measuring mental fatigue using visual analogue scales. It is suggested that future research on mental fatigue in football may benefit from the use of surveys/interviews to understand the true cognitive demands of elite football players. Additionally, future research should aim to reduce the reliance on using visual analogue scales (VAS) to measure mental fatigue as it may be confounded by several response biases. In conclusion, this article highlights the need for mentally fatiguing tasks that adequately represent football-associated mental fatigue and assessments of mental fatigue that minimise the confounding effect of response bias.

Key points

Induced mental fatigue has negatively influenced physical, technical and tactical performance in football-specific tests.

The current mental fatigue literature consists of shortcomings in its present methodological approach.

Future research must seek to understand real-life causations of mental fatigue in elite football, and must also reduce the reliance on the visual analogue scale as a measurement of mental fatigue.

Acknowledgments

The authors wish to thank Adam Beavan and Ruth Boat for editing and proofreading the article.

Compliance with Ethical Standards

Chris Thompson, Job Fransen, Sabrina Skorski, Mitchell R. Smith, Tim Meyer, Steve Barrett and Aaron J. Coutts declare that they have no conflict of interest.

No funding was provided for completion of this manuscript.

1. INTRODUCTION

In recent years, there has been a growing interest in the effects of mental fatigue on performance in team sports, in particular football. Whilst football is clearly physically demanding, it is also likely to be cognitively demanding as a result of the high quantity of decision making and the requirement for rapid information processing during match play [1]. In fact, it has been suggested that with the exception of military combat, team sport performance is more cognitively demanding than any other physical activity [2]. The high technical and tactical demands of football match play with the frequent pressure to meet club expectations may well place a mental demand on an elite football player. Therefore, there is clear rationale for investigating the effects of mental fatigue on football performance.

Currently, six original studies have been conducted to assess the influence of mental fatigue on football related performance, which were recently presented in a review article [3]. Here we summarised that induced mental fatigue negatively influences football-specific physical and technical performance in a lab setting [4-5], with similar effects on technical, but not physical performance in small-sided games [6-7], and impairs decision-making skill [8], despite no influence on visual search behaviour. The most recent of these studies showed that induced mental fatigue resulted in a reduction in team synchronisation and times spent at moderate to high running speeds in small-sided-games [9], the latter being a contradictory finding to previous research [10].

Whilst there is some indication that mental fatigue may be detrimental to football performance, several limitations in the current literature remain to be discussed. More specifically, the aforementioned studies use mentally fatiguing tasks that have questionable ecological validity, and are completed by recreational or sub-elite level football players. In addition, the study designs often rely on subjective measures of mental fatigue, which despite their frequent use, are at risk of being confounded by self-assessment biases [11]. Therefore, this current opinion article aims to critically examine the current methodological practice (inducing and measuring mental fatigue) of mental fatigue research in football, and provide recommendations for future studies in this field.

2. INDUCING MENTAL FATIGUE

At present, all but one of the research articles investigating the role played by mental fatigue in football performance has used either a computerised or paper version of the 30-minute modified Stroop task to induce mental fatigue [4-6, 8-9]. The remaining study used a 20-minute sport specific motor task protocol to induce mental fatigue (please refer to "2.3. *Developing a more ecologically valid mental fatigue protocol*" for a more detailed description) [7]. The Stroop task is a response inhibition/sustained attention task which causes an increased activation of the anterior cingulate cortex, which may cause feelings of mental fatigue due to reduction in transmission of dopamine to the striatum and anterior cingulate cortex [12-13]. Preliminary findings [14] showed that response inhibition tasks such as the Stroop task induce greater perceptions of mental fatigue when compared to a simpler Psychomotor Vigilance Task.

2.1. Limitations of using a modified Stroop task

Despite frequently relating prolonged exposure to a modified Stroop task to a perceived state of mental fatigue, the Stroop protocol demonstrates little relevance to the ecological environment of football. During games, footballers are subjected to environmental, task and individual constraints that allow them to exhibit coordinated behaviour in function of highly dynamic and ever-changing contexts [15]. For example, a player in possession of the ball must constantly use information on the position, running direction and velocities of his teammates (and those of the opposition players), in relation to his own position, while deciding whether to pass, shoot or dribble the ball under high or low amounts of defensive pressure. These collective actions are coordinated relative to the quality and type of playing surface, crowd interaction, and ambient light available during the game. Therefore, players constantly find functional movement solutions to movement problems posed by situations that involve varying and interacting constraints [16]. With this in mind, the current mental fatigue in football studies may lack ecological validity required to make inferences on how mental fatigue that originates from playing football affects sports performance.

2.2. Contextual interference

While playing football is characterised by high degrees of contextual interference (CI, high variability in the consecutive execution of skills), a 30-minute modified Stroop task is more likely associated with much lower amounts of CI. High CI has been associated with high degrees of cognitive engagement and problem solving while low CI tasks are associated with less cognitive engagement and the repetition of a solution to the same problem from trial to trial., For example, a recent study compared the task engagement associated with high and low CI practice schedules (a key-pressing task with two goals: learning the relative timing dimension and learning the absolute timing dimension) and found that greater cognitive effort was associated with high CI than with low CI practice [17]. Furthermore, with increasing time-on-task, task engagement and mental workload decreased more in the low CI practice schedule.

These findings have important implications for research on mental fatigue. First, task engagement and cognitive workloads associated with a repetitive 30-minute modified Stroop task are likely lower than those associated with the constant problem solving based on ever-changing individual, environmental and task constraints associated with football match play. Moreover, the perception of the modified Stroop task from elite football players may be that of boredom and reduced arousal, ultimately providing a different effect on performance in comparison to “football-specific” mental fatigue. Therefore, research investigating the effect of mental fatigue in football should employ mentally fatiguing protocols using tasks with higher degrees of contextual interference that bear more relevance to football match-play.

2.3. Developing a more ecologically valid mental fatigue protocol

To date, one known study has attempted to establish an ecologically valid mentally fatiguing protocol in football research. This consisted of a 20-minute whole-body coordination task which consisted of juggling a tennis ball whilst completing agility ladders, and incorporated motor coordination, sustained attention, cognitive processing and perceptual skills to induce mental fatigue [7]. This was compared to a control condition which consisted of light general aerobic exercises including skipping, jogging, running backwards, and side stepping. Although commendable in its attempt to use a more ecologically valid fatiguing task, methodological considerations such as sport specificity and response bias must be considered. This still points to a pivotal question – what is actually a real-life causation of mental fatigue in football?

2.4. Potential real-life causations of mental fatigue

An editorial article [18] postulated several potential mental stressors resulting from football match play (prolonged vigilance, decision making, constantly receiving and processing information in a dynamic environment) and lifestyle factors (expectations from coaches, supports, sponsors and the media). A further editorial cites the monetary pressure, pressure to perform, plus the influence of media outlets that are quick to glorify the successful and critical to those who fail [19]. However to date, only a limited amount of evidence is available to aid the understanding of football-specific tasks and their relation to mental fatigue.

2.5. Perceived cognitive demands of elite match play

The perceived cognitive demands of elite football (despite the vast amount of decision making and information procession involved in match play) are currently an under-researched area limited to one study. Recent work [20] collected differential RPE (d-RPE) data which consisted of three components (breathlessness (RPE-B), leg muscle exertion (RPE-L) and technical/cognitive exertion (RPE-T)) being measured 15-30 minutes post match by an English Premier League team across one season. Significantly higher RPE-T scores were reported following matches against the higher ranked teams (top six), plus positional data showed that full backs reported substantially higher RPE-T scores than any other position in the team. This single case study, while beneficial, may only be reflective of that team and their style of play. While novel, the use of RPE-T within football at all levels (both match play and training) requires further investigation to assess what influences affect it and if this is reflective of mental fatigue.

2.6. Lifestyle activities

Aside from football-specific cognitive demands, it could be suggested that lifestyle factors may also contribute to mental fatigue. For example, many elite football players are likely to use a car as their mode of transport to and from the club's training facilities, a task which has been frequently reported to induce mental fatigue subjectively and objectively [21-23]. However in these studies the driving protocols lasted between ninety minutes and two hours, and the prevalence and duration of car driving is unknown amongst football players. Another task that may be performed by elite football players is playing video games, which require sustained attention, rapid reaction times and decision making. In one study [24], 32 subjects participated in a 32 team tournament system on the popular franchise video game FIFA 15, with mental fatigue being assessed by performance in a mathematical test (Paced Auditory Serial Addition Test). Whilst it was reported that FIFA 15 gameplay had no effect on mental fatigue, the findings of this study are difficult to interpret as there was no control group and the length and number of games played were not reported. Whilst these studies highlight the cognitive demands of some potential real-life activities, future research must first understand the daily tasks completed by elite footballers leading up to a match, and their potential influence on football related performance.

2.7. Future research

To further understand mental fatigue in elite football, several steps are suggested. Firstly, the use of surveys/interviews to chart the mental demands of high-level football, on and off the field will allow researchers to understand which tasks, if any, players find mentally fatiguing. This will enable the design of more ecologically valid studies to investigate the effect of these "mentally fatiguing" tasks on performance, providing a more realistic understanding of the real-world impact of mental fatigue on football performance. Additionally, future research should attempt to use tasks with high levels of contextual interference to induce feelings of mental fatigue in participants, as these may better reflect the potential levels of mental fatigue experienced by football players during a game.

3. MEASURING MENTAL FATIGUE

3.1. What has been used to measure mental fatigue so far?

All but one of the current studies investigating mental fatigue in football [4-6, 8-9] have utilised a 100 mm Visual Analogue Scale (VAS) [25] to assess subjective mental fatigue. The only exception to this is the remaining study which only used rating of perceived exertion (RPE) to measure perceived workload [7]. In the mental fatigue in football literature, participants completed a VAS before and after the mentally fatiguing/control conditions, plus immediately after the small-sided-games [4-6, 8-9]. Whilst recognising the VAS as a valid way to measure subjective mental fatigue, there are some shortcomings with this method as the primary measurement of mental fatigue in football research. In this section, issues related to bias of the VAS, respondent's uncertainty over the definition of "mental fatigue", and the difficulties associated with masking the aims of mental fatigue research studies using this measurement tool will be discussed. In addition, the use of objective methods as an alternative to measuring mental fatigue will also be examined.

3.2. Response bias and defining "mental fatigue"

In mental fatigue research, the response bias and the difficulty participants have in personally defining the meaning of "mental fatigue" should not be underestimated. The participants in these studies may be prone to different types of response bias. More specifically, participants in studies using VAS to assess mental fatigue may suffer from acquiescence bias, a response bias related to a tendency to agree with questions posed by investigators [11]. Furthermore, participants in these studies may also provide altered responses because they understand they are part of an experiment investigating mental fatigue and therefore want to exhibit behaviour that is suitable in such an experimental context. This type of response bias has been termed 'demand characteristics' [26]. Moreover, participants in studies that investigate mental fatigue may be prone to self-assessment bias, especially if participants lack the ability to truly understand what is meant by 'mental fatigue' (in other words, they may lack metacognition). Therefore it is likely that participants with relatively high or low levels of actual mental fatigue, who are asked to self-report their perceived mental fatigue, over- or underestimate their actual mental fatigue, especially when they lack a clear understanding of the term.

In scientific research, response bias is inevitable, however steps can be taken to minimise its effects. Response bias resulting from demand characteristics can be accounted for by limiting the exposure participants have to the VAS aimed at assessing mental fatigue, as repeated exposure to these subjective ratings might increase the likelihood of participants identifying the true intentions of the experiment. A potential solution may be to adopt a matched group design, rather than a crossover design. However when adopting this design, researchers should be aware that larger sample sizes are required, and groups must be well-matched. Finally, it has been indicated that self-assessment bias can be overcome by increasing participant's metacognitive skills [27]. Therefore, the potential assessment bias associated with the self-reporting of mental fatigue can be overcome by providing a clear and uniform operational definition of mental fatigue and any other subjective measures.

3.3. The use of objective methods to measure mental fatigue

Future mental fatigue in football research may benefit from the use of objective methods which measure psychophysiological (i.e. neural, optical and cutaneous) responses to cognitive tasks. Many examples exist, such as Galvanic Skin Response, Functional Near-Infrared Spectroscopy and pupillary response, which have all assessed mental workload during cognitively demanding tasks [28-30]. However, the most common psychophysiological objective method used to assess mental fatigue is electroencephalography (EEG), a measurement of spontaneous electrical activity in the brain. Across the Sport Science literature, EEG activity has been measured in treadmill endurance performance [31], knee extension exercises [32], golf [33-34], and physically active computer games [35]. Conducting studies in this field proves difficult due to issues caused by excessive movement and sweat, in addition to noise and light disturbances which can negatively influence the data collection [34, 36]. Despite the aforementioned findings in a challenging research area, all of these studies were completed in a static motion or with minimal head movement to enhance the quality of the EEG signal, questioning their practicality to the dynamic nature of football. With the current technology, research in football using EEG may be restricted to measuring the mental demands of zero to minimal movement quantity tasks such as football-specific decision making trials [37] or virtual reality technology.

Aside from psychophysiological measures, cognitive task performance is another common measurement of assessing mental fatigue. Previous investigations that have examined time on task performance across general populations have shown mental fatigue causes a decrement in goal directed attention, impairs performance adjustments after making errors and disturbs anticipation timing [12, 38-39]. Based on the high quantity decision making and rapid information processing demands of team sports, these findings may transfer into a football environment [1]. However further research is required, as the only football-specific study to investigate this reported that cognitive performance (i.e. football decision making) was negatively influenced by induced mental fatigue [8]. Such research may in fact be simpler to implement in an elite football environment in comparison to psychophysiological objective measurements due to its less invasive nature.

Overall, further research is required to elucidate the effects of football-specific tasks on mental fatigue using various objective methods. It must be noted however that studies using psychophysiological objective methods (i.e. EEG) may only be possible to conduct in a laboratory setting with non-elite football players based on the practical difficulties in elite settings. For example the equipment set up times required, invasive properties of the protocol and frequently removing elite players from a congested playing and training schedule may collectively prove too difficult to successfully implement. Developments in technology and/or the emergence of other objective methods (ecologically valid cognitive task performance protocols) may help to allow future research projects to better integrate particularly with elite environments, plus also help to differentiate feelings of mental fatigue and boredom, which is currently challenging when using solely subjective measurements to measure mental fatigue.

4. CONCLUSIONS

To date, available studies suggests induced mental fatigue negatively influences physical, skill, decision making, technical and tactical aspects of football performance, both in isolated performance tests and small-sided-games. However, these studies are limited by tasks with low ecological validity to induce mental fatigue and the use of the VAS to measure mental fatigue, which must be addressed in future research. We suggest that future research should monitor the cognitive stress reported from match play and training via the use of a validated protocol such as d-RPE, an appropriate method to differentiate between physical and cognitive elements of performance. Follow up research should use surveys/interviews with elite football players to better understand the source of mental fatigue. These findings inform the development of mentally fatiguing protocols with greater ecological validity than the existing options.

Future study designs may benefit from reduced reliance on VAS to measure mental fatigue and participants being provided with a clear definition of mental fatigue, which may lower response bias. Whilst objective measurement technology has proven effective in measuring mental workload during cognitively demanding tasks, the current likelihood of its involvement away from a laboratory setting is minimal due to its invasive nature and the inevitable time constraints in (elite) football settings. Therefore, we recommend further studies investigating objective responses to mentally fatiguing protocols in football to consider the use of more practical and less time consuming protocols to help bridge the gap between research and applied settings.

REFERENCES

1. Nédélec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. Recovery in soccer. Sports Med 2012;42:997-1015.
2. Walsh, V. Is sport the brain's biggest challenge? Curr Biol 2014;24:859-60.
3. Smith M, Thompson C, Marcora S, Skorski S, Meyer T, Coutts A. Mental Fatigue and Soccer: Current Knowledge and Future Directions. Sports Med 2018;5:1-8.
4. Smith M, Coutts A, Merlini M, Deprez D, Lenoir M, Marcora SM. Mental fatigue impairs soccer-specific physical and technical performance. Med Sci Sports Exerc 2016;48:267-76. doi:https://doi.org/10.1249/MSS.0000000000000762.
5. Smith M, Fransen J, Deprez D, Lenoir M, Coutts AJ. Impact of mental fatigue on speed and accuracy components of soccer-specific skills. Science and Medicine in Football 2017;1:48-52. doi:10.1080/02640414.2016.1252850.
6. Badin O, Smith M, Conte D, Coutts AJ. Mental fatigue: impairment of technical performance in small-sided soccer games. Int J Sports Physiol Perform 2016;11:1100-5. doi:http://dx.doi.org/10.1123/ijspp.2015-0710.
7. Coutinho D, Gonçalves B, Travassos B, Wong DP, Coutts AJ, Sampaio JE. Mental fatigue and spatial references impair soccer players' physical and tactical performances. Front Psychol 2017;21;8:1645. doi:10.3389/fpsyg.2017.01645.
8. Smith M, Zeuwts L, Lenoir M, Hens N, De Jong LMS, Coutts AJ. Mental fatigue impairs soccer-specific decision-making skill. J Sports Sci 2016;34:1297-304. doi:10.1080/02640414.2016.1156241.
9. Coutinho D, Gonçalves B, Wong D, Travassos B, Coutts AJ, Sampaio J. Exploring the effects of mental and muscular fatigue in soccer players' performance. Hum Mov Sci 2018;58:287-96.
10. Smith M, Marcora S, Coutts A. Mental fatigue impairs intermittent running performance. Med Sci Sports Exerc 2015;47:1682-90.
11. Watson D. Correcting for acquiescent response bias in the absence of a balanced scale: An application to class consciousness. Sociol Methods Res 1992;21:52-88.
12. Lorist M, Boksem M, Ridderinkhof K. Impaired cognitive control and reduced cingulate activity during mental fatigue. Brain Res Cogn Brain Res 2005;24:199-205. doi:https://doi.org/10.1016/j.cogbrainres.2005.01.018.
13. MacDonald A, Cohen J, Stenger V, Carter CS. Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. Science 2000;288:1835-8.
14. Smith MR, Fransen J, Coutts AJ. The effects of three cognitively demanding tasks on psychological and performance indicators of cognitive fatigue. European College of Sports Science; 2014.
15. Araújo D, Davids K, Bennett S, Button C, Chapman G. Emergence of Sport Skills under Constraints. In: Williams AM, Hodges NJ, editors. Skill Acquisition in Sport: Research, Theory and Practice. London: Routledge, Taylor & Francis 2004. pp 409-433.
16. Phillips E, Davids K, Renshaw I, Portus M. Expert performance in sport and the dynamics of talent development. Sports Med 2010;40:271-83.
17 Lelis-Torres N, Ugrinowitsch H, Apolinário-Souza T, Benda RN, Lage, GM. Task engagement and mental workload involved in variation and repetition of a motor skill. Sci Rep 2017;7:14764.
18. Coutts A. Fatigue in football: it's not a brainless task! J Sports Sci 2016;34:1296.
19. Bauman N. The stigma of mental health in athletes: are mental toughness and mental health seen as contradictory in elite sport? Br J Sports Med 2016;50:135-6.
20. Barrett S, McLaren S, Spears I, Ward P, Weston, M. The Influence of Playing Position and Contextual Factors on Soccer Players' Match Differential Ratings of Perceived Exertion: A Preliminary Investigation. Sports 2018;6:13.
21. Zhao C, Zhao M, Liu J, Zheng, C. Electroencephalogram and electrocardiograph assessment of mental fatigue in a driving simulator. Accid Anal Prev 2012;45:83-90.

22. Ting P, Hwang J, Doong J, Jeng MC. Driver fatigue and highway driving: A simulator study. Physiol Behav 2008;94:448-53.
23. Lal SK, Craig A. Driver fatigue: electroencephalography and psychological assessment. Psychophysiology 2002;39:313-21.
24 Aliyari H, Kazemi M, Tekieh E, Salehi M, Sahraei H, Daliri MR, Agaei H, Minaei-Bidgoli B, Lashgari R, Srahian N, Hadipour MM. . The effects of fifa 2015 computer games on changes in cognitive, Hormonal and brain waves functions of young men volunteers. Basic Clin Neurosci 2015;6:193.
25. Lee K, Hicks G, Nino-Murcia G. Validity and reliability of a scale to assess fatigue. Psychiatry Res 1991;36:291-8.
26. Orne M. Demand characteristics and the concept of quasi-controls. Artifacts in Behavioral Research. New York: Academic Press; 1969.
27. Kruger J, Dunning D. Unskilled and unaware of it: how difficulties in recognizing one's own incompetence lead to inflated self-assessments. J Pers Soc Psychol 1999;77:1121.
28. Widyanti A, Muslim K, Sutalaksana I. The sensitivity of Galvanic Skin Response for assessing mental workload in Indonesia. Work 2017;56:111-7.
29. Li K, Pan B, Gao Y, Ruan Z, Li T. A novel method to estimate oxygen saturation of the internal jugular vein blood. International Society for Optics and Photonics 2016;96981F-96981F.
30. Kahneman D, Tursky B, Shapiro D, Crider A. Pupillary, heart rate, and skin resistance changes during a mental task. J Exp Psychol 1969;79:164.
31. Brownsberger J, Edwards A, Crowther R, Cottrell D. Impact of mental fatigue on self-paced exercise. Int J Sports Med 2013;34:1029-36.
32. Baumeister J, Reinecke K, Schubert M, Schade J, Weiss M. Effects of induced fatigue on brain activity during sensorimotor control. Eur J Appl Physiol 2012;112:2475-82.
33. Baumeister J, Reinecke K, Liesen H, Weiss M. Cortical activity of skilled performance in a complex sports related motor task. Eur J Appl Physiol 2008;104:625.
34. Reinecke K, Cordes M, Lerch C, Koutsandréou F, Schubert M, Weiss M, Baumeister J. From lab to field conditions: a pilot study on EEG methodology in applied sports sciences. Appl Psychophysiol Biofeedback 2011;36:265-71.
35. Baumeister J, Reinecke K, Cordes M, Lerch C, Weiß M. Brain activity in goal-directed movements in a real compared to a virtual environment using the Nintendo Wii. Neurosci Lett 2010;481:47-50.
36. Britton J. Adult EEG. Clin Neurophysiol 2016;31:76.
37. Vaeyens R, Lenoir M, Williams AM, Mazyn L, Philippaerts RM. The effects of task constraints on visual search behavior and decision-making skill in youth soccer players. J Sport Exerc Psychol 2007;29:147-69.
38. Boksem M, Meijman T, Lorist M. Effects of mental fatigue on attention: an ERP study. Brain Res Cogn Brain Res 2005;25:107-16. doi:https://doi.org/10.1016/j.cogbrainres.2005.04.011.
39. Duncan MJ, Fowler N, George O, Joyce S, Hankey J. Mental fatigue negatively influences manual dexterity and anticipation timing but not repeated high-intensity exercise performance in trained adults. Res Sports Med 2015;23:1-3.

5 – HOW RELEVANT IS THE MODIFIED STROOP TASK IN MENTAL FATIGUE IN FOOTBALL RESEARCH?

5.1 – Rationale

In five of the six investigative studies to measure the impact of induced mental fatigue on football-specific performance, the modified Stroop task has been used (Coutinho et al., 2018; Smith et al., 2017; Badin, Smith, Conte, & Coutts 2016; Smith et al., 2016a; Smith et al., 2016b). As highlighted in chapter 4, the modified Stroop task was suggested to be an inappropriate task to induce mental fatigue in football due to its low contextual interference, and subsequent irrelevance to the high contextual interference nature of football. Indeed, the modified Stroop task may incur boredom, a similar construct to mental fatigue. Such a claim is speculative and requires further research. Football is also a sport which requires a quick and accurate response to implicit and explicit sources of information, and little is known on how mental fatigue impacts this ability. In addition, it remains unknown if mental fatigue is a transient or chronic sensation. The aim of the following study was to elucidate the effects of a modified Stroop task on mental fatigue and boredom, congruent and incongruent reaction times, followed by the investigation of a short rest period on perceived recovery.

5.2 - Understanding the influence of a cognitively demanding task on motor response times and subjective mental fatigue/boredom.

This section contains the following published manuscript:

Thompson, C., Fransen, J., Beavan, A., Skorski, S., Coutts, A., & Meyer, T. (2020). Understanding the influence of a cognitively demanding task on motor response times and subjective mental fatigue/boredom. *Brazilian Journal of Motor Behavior*, *14*(01), 33-45.

The citations and references of this manuscript are formatted to the requirements of the Brazilian Journal of Motor Behavior. These citations only relate to the reference list in this thesis chapter and not to the reference list included at the end of this thesis.

Title: Understanding the influence of a cognitively demanding task on motor response times and subjective mental fatigue/boredom.

Chris Thompson[1, 2], Job Fransen[2], Adam Beavan[1, 2, 3], Sabrina Skorski[1], Aaron J. Coutts[2] & Tim Meyer[1].

1 - Institute of Sport and Preventive Medicine, Saarland University, Saarbrücken, Germany.

2 - Sport and Exercise Discipline Group, Faculty of Health, University of Technology Sydney, Moore Park, Australia.

3 - German Football Association (Deutscher Fußball-Bund; DFB), Frankfurt, Germany.

Corresponding author

Chris Thompson

Telephone - +49 (0) 681 302 70413 **Email -** chris.thompson@uni.saarland.de

Affiliation addresses

Saarland University – Institute of Sports and Preventive Medicine, Saarland University, Building 8.2, 66123 Saarbrücken, Germany.

University of Technology, Sydney – Moore Park Rd & Driver Ave, Moore Park NSW 2021, Australia.

Deutscher Fußball-Bund - Deutscher Fußball-Bund e.V. (DFB), Hermann-Neuberger-Haus, Otto-Fleck-Schneise, 660528 Frankfurt/Main, Germany.

Author ORCID

Chris Thompson: 0000-0001-5333-3616

Job Fransen: 0000-0003-3355-1848

Sabrina Skorski: 0000-0001-8449-6872

Aaron Coutts: 0000-0002-1782-7691

Tim Meyer: 0000-0003-3425-4546

Keywords: mental fatigue; boredom; Stroop.

Abstract

Several methods are used to induce mental fatigue; most predominantly the modified Stroop task. Whilst this task has demonstrated an ability to induce mental fatigue, its relevance to daily lifestyle tasks is questionable. The purpose of the current study was to investigate the influence of exposure to a 30-min modified Stroop task on subjective ratings of mental fatigue, mental effort and boredom, along with participants' ability to use congruent and inhibit incongruent precues in a choice reaction time task (CRTT), and the impact of a 5-min rest period from mentally fatiguing activity. Using a 0-10 cm arbitrary unit (AU) scale, significantly higher subjective ratings of pre-post condition mental fatigue (pre: 2.43±1.31 AU, post: 6.42±2.08 AU) and boredom (PRE: 1.65±1.49 AU, POST: 5.03±2.92 AU) were reported following the modified Stroop task condition compared to the control (reading magazines) condition mental fatigue (PRE: 1.62±1.17 AU, POST: 2.10±0.92 AU) and boredom (PRE: 1.94±1.52 AU, POST: 3.32 ± 1.66 AU). In addition, a 5-min rest was not enough to return to subjective baseline measures of mental fatigue (POST-5: 5.26±1.49 AU) and boredom (POST-5: 3.85±2.07 AU). No significant differences were found between conditions for the extent to which participants' response times were affected by congruent (p=0.481) or incongruent (p=0.225) precues. Future research must further investigate the practicality of the modified Stroop task in real-world settings, adopt cognitive activities with greater task relevance with higher contextual interference for greater ecological validity, and elucidate the impact of rest on recovery from mental fatigue.

Keywords

Mental fatigue, boredom, Stroop.

1. Introduction

To induce mental fatigue, previous studies have used a range of cognitively demanding tasks. These include (but are not limited to) a 90-min AX-Continuous Performance Task (Marcora et al., 2009, MacMahon et al., 2014, Smith et al., 2015), a 60-min Go/NoGo Task (Kato, Endo & Kizuka, 2009), a 2-hour Eriksen Flanker test (Faber et al., 2012; Lorist et al., 2005), a blocked 4 x 10-min Sustained Attention to Response Task (Dillard et al., 2014), and most commonly, a 30-min modified Stroop task (Smith et al., 2018; Van Cutsem et al., 2017). The modified Stroop task is a response inhibition/sustained attention task that elevates the activation of the anterior cingulate cortex (MacDonald, Cohen, Stenger et al., 2000), which appears to play a significant role in the onset of mental fatigue. It has been theorised that following prolonged exposure to a cognitively demanding task such as the modified Stroop task, mental fatigue results from a reduction in the transmission of dopamine to the striatum and anterior cingulate cortex (Martin et al., 2018; Lorist et al., 2005). Based on the current evidence, the use of the modified Stroop task can be regarded as a feasible activity to generally induce mental fatigue.

A limitation of the modified Stroop task is that it may not be representative of how mental fatigue is experienced in real life settings (Thompson et al., 2018). For instance, a driver would not complete a modified Stroop task before entering a car, nor would an athlete before a competition, making the practical validity of using a modified Stroop task questionable in high contextual situations. The repetitive nature of continually solving the same task problem may become monotonous and evoke lower levels of contextual interference than real life tasks such as driving, military activity and sport. Lelis-Torres et al., (2017) compared the task engagement associated with high and low contextual interference practice schedules (a key-pressing task with two goals: learning the relative timing dimension and learning the absolute timing dimension) and found that greater cognitive effort was more closely associated with high contextual interference than with low contextual interference practice (Lelis-Torres et al., 2017). It has also been proposed that if a task is perceived to be repetitive, meaningless and does not challenge the subject, it may result in boredom (Pattyn et al., 2008). Pattyn et al., (2008) explain an “underload” and “overload” performance hypothesis, where a cognitive task with an “underload” (i.e. low cognitive demand) is subjectively associated with mind wandering (boredom), whilst an “overload” task consists of a subjectively high cognitive demand when completing the NASA-TLX test (mental fatigue). It is plausible that the modified Stroop task may be regarded as boring by participants, but it remains unknown if impaired performance levels are partly caused by boredom due to low intrinsic motivation to engage in the task, rather than the demands of the task itself (Thompson et al., 2018; Hockey, 2011). Despite the widespread use of a 30-min modified Stroop task as a means of inducing mental fatigue in the literature (Smith et al., 2018; van Cutsem et al., 2017), its difference or independence to boredom is yet to be investigated.

We recently identified the need to supplement subjective perceptions of mental fatigue with more objectively quantifiable assessments (Thompson et al., 2018). One solution could be to assess the effect of mental fatigue on motor response times. Motor response times represent the ability of an individual to detect relevant information sources, process that information and use it to generate an appropriate movement response. Moreover, response times represent the difference between the moment a stimulus appears and the subsequent execution of a motor response (Schmidt & Lee, 2013). It is understood that an increase in response times represents decrements in neuromuscular performance. Therefore, response time paradigms may be able to detect inefficiencies of the motor control system as a result of fatigue, including mental fatigue (Kato et al., 2009; Lorist et al., 2009). However, simple or even choice response time tasks also bear little relevance to performance in cognitively demanding activities such as driving or sport. Alongside being able to respond rapidly to a single stimulus (i.e. simple reaction time) or deciding between different responses based on a variety of stimuli (i.e. choice reaction time), such populations need to demonstrate fast and accurate decision making that includes the ability to use advanced information or suppress irrelevant stimuli. For example, a soccer player may decide to pass the ball to an available teammate but choose not to when observing that that teammate is suddenly covered by a defender or another teammate is in a better position to receive the ball.

Limited evidence is also available on the amount of rest required to overcome subjective feelings of mental fatigue. A break (and not necessarily sleep) from a mentally fatiguing task will result in some recovery (Balkin & Westensten, 2011), but the duration of that break is unknown. Understanding the timing and duration of a rest break required to diminish the effects of mental fatigue is a crucial step to further understand the relationship between mental fatigue and motor performance, as it may help mitigate the potentially negative effects of mental fatigue on performance.

Therefore, the aim of the current study was twofold. First, to investigate the effects of a modified Stroop task on participants' ability to use precued information in a choice response time task in which participants execute or suppress a motor response based on a congruent or incongruent precue preceding the stimulus. The secondary aim of the study was to understand the relationship between measures of mental fatigue, mental effort and boredom to understand whether the modified Stroop task represents an appropriate method to induce mental fatigue. It was hypothesised that 1) a 30-min modified Stroop task would negatively affect the ability for participants to inhibit a motor response, 2) a 30-min modified Stroop task would significantly increase subjective ratings of mental fatigue, mental effort and boredom, and 3) an acute rest period (5-min) from cognitive activity would be sufficient to elicit significant reductions in subjective ratings of mental fatigue.

2. Methodology

2.1. Participants

Fifteen university students aged 18 – 27 years (24.3 ± 2.3 years) with normal or corrected to normal vision volunteered to participate in the study. Ethical approval for all procedures was attained from the Saarland University Ethics Committee under the Declaration of Helsinki.

2.2. Procedures

The study outline consisted of two separate protocols completed in a randomised counter-balanced order. Participants were informed that they would be completing a computer task and a reading task on two separate occasions, four weeks apart, in the same location at the same time of day. Following this, participants provided their informed consent to participate. In both conditions, participants were placed in a rigid chair facing a desktop table containing a laptop computer and a customised four button controller. The controller was placed `between the computer and the participant, precisely 8 cm from the edge of the computer. The dominant hand of the participant was placed flat on the table 3 cm away from the controller system, and the non-dominant hand was situated either on their thigh or the table. The familiarisation protocol consisted of a brief (12 trials) congruent version of the choice reaction time task (CRTT), a 60s trial of the modified Stroop and a description of the reading task.

A pre-task (PRE) visual analogue scale (VAS) for mental fatigue and boredom were then completed, followed by the first CRTT trial. Next, participants were exposed to 30-min of either the modified Stroop task or the magazine reading condition. The test was completed with the researcher seated two metres behind the participant to ensure study compliance. Immediately post-task (POST), participants again completed VAS for mental fatigue, boredom and mental effort, which corresponded to the amount of perceived mental effort that was required to complete the preceding task. The CRTT was then immediately completed for a second time, followed by a five minute rest period where the participant sat alone in the testing room with the instructions to relax and avoid any task engagement. To facilitate this, personal items (i.e. mobile phones, laptops, mobile phones) were securely stored outside of the testing room during the test. Finally, participants completed a final VAS for mental fatigue and boredom immediately following the five minute rest period (POST-5).

2.3. Response inhibition

The response inhibition task (Unity, Version 5.4.0f3, 2016) consisted of 24 trials grouped into 12 congruent and 12 incongruent trials on a 14.3" laptop screen, lasting a total of three minutes. Across all trials, a three second countdown was followed by the appearance of four white circles with a black outline (all of which consist of a diameter of 512 pixels and an edge width of 5 pixels) presented in a horizontal position. Following a randomised two – four second delay, one of the four circles turned yellow. The participant was required to accurately press the button on the controller (Lioncast, Berlin, Germany) which corresponded to the yellow circle as quickly as possible. The precue in the congruent trials was a small black dot (26 pixels) which appeared in a white circle (512 pixels) 86 ms before it turned yellow. Conversely in the incongruent trials, the same black dot acted as a decoy by appearing in a white circle 86 ms before an opposing circle turned yellow. In both trials, the precue was presented on the screen for a duration of 43 ms according to the procedures outlined in one of the experimental conditions of an implicit precue paradigm used by Fransen et al., (under review), but adapted to include a measure of response inhibition.

2.4. Modified Stroop task

In the modified Stroop task, four words ("blue", "yellow", "red", "green") repeatedly appeared on a Windows Powerpoint Presentation document screen in a randomised fashion. The correct answer in the trial will be the colour of the ink (blue, yellow, red, green), and not the word. However, to increase task difficulty, any word presented in red ink the correct response corresponds to the meaning of the word. The test was translated into German, the first language of the participants. Each participant completed 900 trials, each separated by 2000 ms. All trials required a verbal response to the researcher, who was seated two metres behind the participant to avoid acting as a visual distraction during the test.

2.5. Control condition

In the control condition, participants were presented with a selection of four magazines of varying topics to read (sport, cars, fashion and lifestyle). They were instructed to read any of the chosen magazines for a period of 30-min whilst seated in front of the lead researcher. The choice of magazines was influenced by previous pilot testing.

2.6. Visual analogue scale

A visual analogue scale (VAS) was used to measure three subjective parameters; 1) boredom ("Please state your current level of boredom"), 2) mental fatigue ("Please state your current level of mental fatigue") and 3) mental effort ("Please state the mental effort of the task you have just completed"). On a 100 mm horizontal line scale, the answer selection ranged from "none at all" to "maximal". Using a paper version, participants were instructed to draw a vertical line over a selected area of the scale to select their subjective rating of each parameter, which was later measured by the lead researcher to create arbitrary units (AU).

2.7. Statistical analyses

To investigate the effect of the experimental condition (i.e. the reading task (control) or the modified Stroop task and timing of the measurement (PRE, POST & POST-5) on both cognitive (mental fatigue, mental effort and boredom) and response times (congruent and incongruent task performance), a series of linear mixed models was developed. A stepwise approach was used in which additional predictors were added to the model with each step, and model fit was evaluated using the Akaike's Information Criterion (AIC), observation of increases in degrees of freedom, a -2 log-likelihood ratio test and the normal distribution of the models' residuals. The cognitive variables and response times were entered as response variables in each of the four linear mixed models. The experimental condition and the time of measurements (fixed factors) were entered as predictor variables in addition to each participant's unique identifier (random factor) to account for the random variance associated with the clustering of participants' repeated measures within each participant. Prior to the analysis, pre-modelling assumption checks (i.e. linearity of relationships, homogeneity of variance) were carried out. Following the analysis, the appropriateness of each model was analysed through the normality of the distribution of model residuals using visual inspection through boxplots and a Shapiro-Wilk test. The significance level for the -2 log-likelihood ratio tests was set at $p < 0.05$, and an estimate precision was provided using Wald-based 95% confidence intervals.

3. Results

The best fit was achieved using a random intercepts model (participant ID) and through the introduction of a time*experimental condition interaction effect to explain the variance in mental fatigue and boredom. However, no significant predictors of congruent and incongruent response times were observed in this study ($p>0.05$). As mental effort was only recorded during the post-test, a random intercept model with the experimental condition as the only fixed effect best explained the variance in mental effort (AIC = 112.42, df = 1-,4, p = <0.001, conditional explained variance = 75%). A random intercepts model that incorporated both the condition and time main effects as well as the condition*time interaction effect best explained the variance in subjective ratings of mental fatigue and boredom (mental fatigue: AIC = 326.39, df = 2,8, p = <0.001, conditional explained variance = 66%; boredom: AIC = 371.14, df = 3,8, p = <0.021, conditional explained variance = 54%). All model parameters organised by dependent variable can be found in Table 1.

As shown in Figure 1, a significant condition*time interaction effect ($p<0.001$) was observed in ratings of mental fatigue. Mental fatigue values increased from PRE (2.43 ± 1.31 AU) to POST (6.42 ± 2.08 AU; $p<0.01$) in the modified Stroop task condition. Furthermore, despite the POST-5 mental fatigue values decreasing (5.26 ± 1.49 AU; $p<0.01$) from the POST test values, they still remained higher ($p<0.01$) compared to the PRE test values within the Stroop task condition. Contrastingly no observable differences ($p>0.05$) were recorded in the control condition across the PRE, POST or POST-5 time points (see Table 1).

Subjective rating of boredom followed a similar trend to mental fatigue for both conditions, and a significant condition*time interaction effect ($p=0.021$) was also observed. In the modified Stroop condition, ratings of boredom increased from PRE (1.65 ± 1.49 AU) to POST (5.03 ± 2.92 AU; $p<0.01$). Aligned with the trends of mental fatigue ratings, POST-5 boredom values (3.85 ± 2.07 AU) also decrease from POST values, but remained higher ($p<0.01$) from the initial PRE test values. Ratings of boredom were also similar to the ratings of mental fatigue in the control condition, where no significant differences ($p>0.05$) were observed across PRE, POST, and POST-5 time points.

Furthermore, a conditional main effect ($p<0.001$) was observed for mental effort scores recorded at POST, as participants reported higher ratings of mental effort in the modified Stroop condition (6.67 ± 1.72 AU) compared to the control condition (1.87 ± 1.05 AU). Lastly, there were no differences in congruent or incongruent response times between the modified Stroop task and control conditions (see Table 1). The estimated marginal means, standard errors and associated 95% confidence intervals derived from the best fitting models for each dependent variable are presented in Table 2.

	AIC	p (-2 log likelihood ratio test)	Chi^2	df	R^2 fixed only (%)	Conditional R^2 random + fixed (%)
Congruent						
Final Model: Congruent ~ 1 + (1|ID)						
Condition main effect	-210.18	0.733	0.116	1,4	< 0.1	64
Time main effect	-210.48	0.519	0.416	1,4	0.2	64
Time + Condition main effect	-208.59	0.766	0.533	2,5	0.3	64
Interaction effect	-208.53	0.481	2.468	3,6	1.4	65
Incongruent						
Final Model: Incongruent ~ 1 + (1|ID)						
Condition main effect	-220.48	0.611	0.259	1,4	0.1	78
Time main effect	-220.26	0.848	0.037	1,4	< 0.1	78
Time + Condition main effect	-218.52	0.862	0.296	2,5	0.1	77
Interaction effect	-220.28	0.225	4.061	3,6	1.4	78
Mental fatigue						
Final Model: Mental fatigue ~ Time*ExpCond + (1|ID)						
Condition main effect	370.31	<0.001	43.663	1,4	38	38
Time + Condition main effect	346.80	<0.001	27.514	2,6	54	54
Interaction effect*	326.39	<0.001	24.412	2,8	64	66
Mental effort						
Final Model: Mental effort ~ ExpCond + (1|ID)						
Conditional main effect*	112.42	<0.001	41.801	1,4	75	75
Boredom						
Final Model: Boredom ~ Time*ExpCond + (1|ID)						
Condition main effect	399.52	0.134	2.248	1,4	2	29
Time main effect	374.87	<0.001	28.891	2,5	19	50
Time + Condition main effect	373.54	0.068	3.328	1,6	21	51
Interaction effect*	371.14	0.021	9.7301	3,8	24	54

Table 1. Models that explain the effect of condition and time of measurement on participants' cognitive and physical variables. * indicates the best fitting model based on AIC value and -2log-likelihood ratio test. ID = individual participant identification number, Time = time of measurement (i.e. pre-test, post-test or post-test + 5 minutes break), ExpCond = experimental condition (i.e. Control or Stroop).

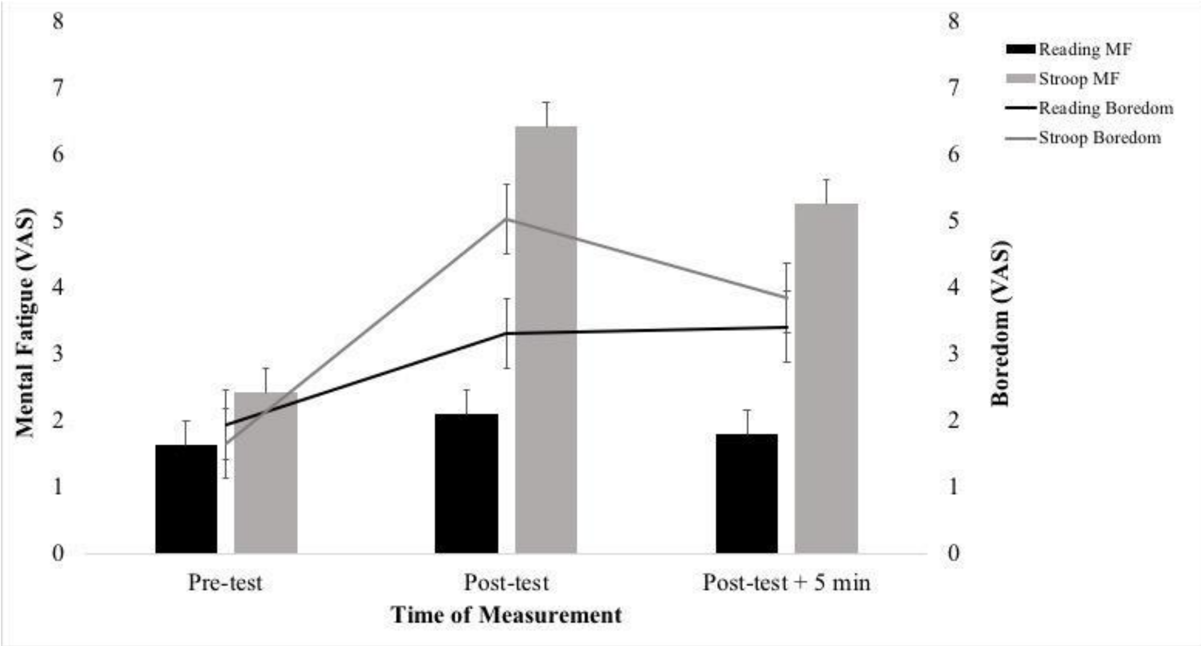


Figure 1 – Pre and post VAS ratings of subjective mental fatigue and boredom.

Experimental Condition	Time of Measurement	Estimate	Std. Error	Lower CI	Upper CI	t value
Congruent (sec)						
Reading	Pre-test	0.618	0.0132	0.591	0.645	46.750
Reading	Post-test	0.612	0.0132	0.585	0.632	-0.509
Stroop	Pre-test	0.604	0.0132	0.577	0.632	-1.200
Stroop	Post-test	0.620	0.0132	0.593	0.647	1.358
Incongruent (sec)						
Reading	Pre-test	0.635	0.0143	0.605	0.664	44.531
Reading	Post-test	0.621	0.0143	0.591	0.650	-1.491
Stroop	Pre-test	0.625	0.0143	0.596	0.655	-0.990
Stroop	Post-test	0.637	0.0143	0.607	0.666	1.914
Mental Fatigue VAS (au)						
Reading	Pre-test	1.627	0.364	0.903	2.351	4.470
Reading	Post-test	2.100	0.364	1.376	2.824	0.946
Reading	Post-test + 5 min	1.793	0.364	1.069	2.517	0.333
Stroop	Pre-test	2.427	0.364	1.703	3.151	1.599
Stroop	Post-test	6.420	0.364	5.696	7.144	4.973
Stroop	Post-test + 5 min	5.260	0.364	4.536	5.984	3.768
Mental Effort VAS (au)						
Reading	Post-test	1.873	0.369	1.118	2.628	5.083
Stroop	Post-test	6.673	0.369	5.918	7.428	9.209
Boredom VAS (au)						
Reading	Pre-test	1.947	0.525	0.890	3.003	3.708
Reading	Post-test	3.320	0.525	2.264	4.376	2.387
Reading	Post-test + 5 min	3.413	0.525	2.357	4.470	2.549
Stroop	Pre-test	1.653	0.525	0.597	2.710	-0.510
Stroop	Post-test	5.033	0.525	3.977	6.090	2.466
Stroop	Post-test + 5 min	3.847	0.525	2.790	4.903	0.893

Table 2. Least square means, 95% confidence intervals (CI), standard error (Std. Error), t-values and random effect parameters from four linear mixed models investigating the effects of condition and time of measurement on participants' cognitive and physical variables. VAS = Visual Analogue Scale.

4. Discussion

Historically, many different cognitive tasks have been used to induce mental fatigue (Smith et al., 2015; Dillard et al., 2014; MacMahon et al., 2014; Faber et al., 2012; Kato et al., 2009; Marcora et al., 2009; Lorist et al., 2005), with the 30-min modified Stroop task being the predominant method (Smith et al., 2018; van Cutsem et al., 2017). This has recently been challenged for its low contextual interference and irrelevance to daily tasks (Thompson et al., 2018), which may lead to low intrinsic motivation to engage in the activity and ultimately subjective boredom. Furthermore, the amount of time required to rest from mentally fatiguing tasks is yet to be investigated in the literature. Our study has demonstrated that in comparison to a control condition (reading magazines), 30-min exposure to the modified Stroop resulted in significantly greater subjective mental fatigue, mental effort and boredom, but did not significantly impair motor task performance. Moreover, a 5-min rest period was not enough to provide a full subjective recovery of mental fatigue and boredom. The results of the current study provide an insight into the applicability of the modified Stroop task in inducing mental fatigue, impact of rest from mentally fatiguing activity, and future suggestions for inducing mental fatigue in subsequent research.

The primary finding in the current study was the greater subjective boredom reported following the modified Stroop task condition in comparison to the control task. These findings support the argument that the modified Stroop task is boring, and this boredom may subsequently influence the perception of mental fatigue. Ultimately the modified Stroop task may not be a relevant task to induce mental fatigue due to its irrelevance to many real-world tasks (Thompson et al., 2018). It has been suggested that boredom is linked to monotony (Perkins, 1985), and that impaired task performance is associated with low intrinsic attractiveness of the task (Hockey, 2011). In the present study, the modified Stroop task is likely to have been met with low intrinsic motivation and task engagement due to its irrelevance to daily activities and no perceived reward. The nature of the task is highly repetitive with little variation and low contextual interference. Indeed, low contextual interference tasks provide a lesser cognitive engagement than high contextual interference tasks (Lelis-Torres et al., 2017), and likely provides a cognitive “underload” (Pattyn et al., 2008). Here it was theorised that compared to “overload” tasks (i.e. high cognitive engagement), an “underload” task provides a reduced cognitive challenge and is associated with mind wandering (i.e. boredom). This evidence suggests that whilst the modified Stroop task may bear a resemblance to some real-world tasks with prolonged vigilance and low cognitive engagement (i.e. repetitive factory or office-based tasks), more dynamic tasks (e.g. sport, military activity) require a more ecologically valid protocol to induce mental fatigue in future studies. To develop such protocols, future research must further understand real-world (such as lifestyle or task specific) cognitive demands experienced by individuals in dynamic task performers.

Despite significant increases in subjective mental fatigue and boredom, congruent and incongruent response times were unaffected by exposure to a 30-min modified Stroop task. The results are contrary to the hypothesis and somewhat surprising given the available literature. It has previously been reported that participants performing a 60-min Go/NoGo recorded significantly greater reaction times, number of errors, and mental fatigue scores with time spent on the task (Kato et al., 2009). These results demonstrate a decrement in response inhibition performance, along with an impairment of the intensity of response execution. Additionally, when exposed to a 30-min modified Stroop task, Smith et al., (2016) demonstrated very likely lower decision-making accuracy and likely higher response times in a soccer specific soccer decision making test in comparison to a control condition (reading magazines). There may be multiple explanations as to why these results differed to the current study. Firstly, the 60-min Go/NoGo task used by Kato et al., (2009) was twice the duration of the 30-min modified Stroop task. In addition, Smith et al., (2016) used a soccer-specific task in a sample of soccer players, thus using a sport-specific stimulus may complicate the comparison of the results of these two studies. However, the fact that congruent and incongruent response times remained unaffected in the current study, increases in subjective ratings of mental fatigue and boredom may be due to the modified Stroop task's inability to elicit true mental fatigue or the ability to use implicit information to inform action is unaffected by mental fatigue.

The present findings show that a five minute rest period following the modified Stroop task significantly reduced subjective ratings of mental fatigue and boredom but did not fully dissipate to baseline levels after the rest period. Despite the inability to fully recover, the study shows that even a five minute period was enough to significantly reduce subjective mental fatigue. This suggests that mental fatigue is transient and stimulus dependent, which supports the suggestion that mental fatigue in many real-world settings is not as problematic as theorised (unless cognitive activities are followed by a short rest and further cognitive activity which may elicit more chronic states of mental fatigue). Alternatively, as each subject in the current study participated in the protocol at varying times (but consistent within each subject) of the day (morning to early evening), the ability to subjectively recover from the modified Stroop may have been influenced by this variability and future study designs interested in the acute effects of mental fatigue on performance should aim to assess each participant at the same time of the day. Other considerations in relation to this are the present workload experienced by the participants, as well as sleep duration, which was not measured in the study. Additionally, whilst periods of rest or time away from cognitive tasks have been previously advocated as methods to reduce feelings of mental fatigue (Wesensten, Belenky et al., 2004, Balkin and Wesensten 2011), the timing and dosing of recovery following mentally fatiguing tasks remains unknown. However, it must be emphasised that clearly interpreting post task subjective measurements of mental fatigue and boredom is challenging. Participants in the current study were required to sit alone with no stimulation (i.e. in silence with no mobile phone/laptop access), which in longer periods may even further exacerbate subjective feelings of mental fatigue and boredom, which has been likened to a high level of frustration (Hill & Perkins, 1985).

In summary, this study demonstrated that despite greater subjective mental fatigue, boredom and mental effort in the modified Stroop condition, participants' ability to use congruent and suppress incongruent precues was maintained in comparison to a control condition. Moreover, a five minute break reduced subjective mental fatigue and boredom in the modified Stroop condition, but still resulted in an incomplete recovery. We suggest that the modified Stroop task may not be a "one size fits all" approach to inducing mental fatigue when considering the level of contextual interference of a particular task. High contextual interference tasks have been associated with high degrees of cognitive engagement and problem solving while low contextual interference tasks are associated with less cognitive engagement and the repetition of a solution to the same problem from trial to trial (Lelis-Torres et al., 2017). Whilst the low contextual interference associated with the modified Stroop task may resemble monotonous repetitive tasks such as some factory operation and office working roles, other tasks with higher levels of contextual interference may require greater ecological validity. In the military for example, rifle marksmanship is a high pressure task which requires intact motor and cognitive system functioning (Chung et al., 2006). Furthermore in sport, athletes perform in highly dynamic and ever-changing contexts under environmental, task and individual constraints (Araújo et al., 2004). To allow for further understanding of how such complex cognitive tasks are influenced by mental fatigue, it is recommended that future research understands real-life activities experienced by complex task performers. This will in turn create more ecologically valid protocols which bear a greater resemblance than the modified Stroop task.

Declarations of interest: none.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Balkin, T. J. and N. J. Wesensten (2011). Differentiation of sleepiness and mental fatigue effects. Cognitive fatigue: Multidisciplinary perspectives on current research and future applications. P. L. Ackerman. Washington, DC, American Psychological Association**:** 47-66.

Chung, G. K., Delacruz, G. C., de Vries, L. F., Bewley, W. L., & Baker, E. L. (2006). New directions in rifle marksmanship research. *Military Psychology*, *18*(2), 161-179.

Dillard, M. B., Warm, J. S., Funke, G. J., Funke, M. E., Finomore Jr, V. S., Matthews, G., Shaw, T.H., & Parasuraman, R. (2014). The sustained attention to response task (SART) does not promote mindlessness during vigilance performance. *Human Factors*, *56*(8), 1364-1379.

Faber, L. G., Maurits, N. M., & Lorist, M. M. (2012). Mental fatigue affects visual selective attention. *PLoS ONE*, *7*(10), e48073.

Fransen, Novak, Turner, Tosi Rodrigues, Barela. Implicit precues are an affordable for action in a choice response time task. Unpublished results.

Hill, A. B., & Perkins, R. E. (1985). Towards a model of boredom. *British Journal of Psychology*, *76*(2), 235-240.

Hockey, G. R. J. (2011). A motivational control theory of cognitive fatigue. *Cognitive fatigue: Multidisciplinary Perspectives on Current Research and Future Applications*, 167-87.

Kato, Y., Endo, H., & Kizuka, T. (2009). Mental fatigue and impaired response processes: event-related brain potentials in a Go/NoGo task. *International Journal of Psychophysiology*, *72*(2), 204-211.

Lelis-Torres, N., Ugrinowitsch, H., Apolinário-Souza, T., Benda, R. N., & Lage, G. M. (2017). Task engagement and mental workload involved in variation and repetition of a motor skill. *Scientific Reports*, *7*(1), 14764.

Lorist, M. M., Bezdan, E., ten Caat, M., Span, M. M., Roerdink, J. B., & Maurits, N. M. (2009). The influence of mental fatigue and motivation on neural network dynamics; an EEG coherence study. *Brain Research*, *1270*, 95-106.

Lorist, M. M., Boksem, M. A., & Ridderinkhof, K. R. (2005). Impaired cognitive control and reduced cingulate activity during mental fatigue. *Cognitive Brain Research*, *24*(2), 199-205.

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science*, *288*(5472), 1835-1838.

MacMahon, C., Schücker, L., Hagemann, N., & Strauss, B. (2014). Cognitive fatigue effects on physical performance during running. *Journal of Sport and Exercise Psychology*, *36*(4), 375-381.

Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *Journal of Applied Physiology*, *106*(3), 857-864.

Martin, K., Meeusen, R., Thompson, K. G., Keegan, R., & Rattray, B. (2018). Mental fatigue impairs endurance performance: a physiological explanation. *Sports Medicine*, 1-11.

Pattyn, N., Neyt, X., Henderickx, D., & Soetens, E. (2008). Psychophysiological investigation of vigilance decrement: Boredom or cognitive fatigue? *Physiology & Behavior*, *93*, 369-378.

Schmidt, R., & Lee, T. (2013). *Motor learning and performance, 5E with web study guide: from principles to application*. Human Kinetics. Page 22 – 23.

Smith, M. R., Coutts, A. J., Merlini, M., Deprez, D., Lenoir, M., & Marcora, S. M. (2016). Mental fatigue impairs soccer-specific physical and technical performance. *Medicine and Science in Sports and Exercise*, *48*(2), 267-276.

Smith, M. R., Fransen, J., Deprez, D., Lenoir, M., & Coutts, A. J. (2017). Impact of mental fatigue on speed and accuracy components of soccer-specific skills. *Science and Medicine in Football*, *1*(1), 48-52.

Smith, M. R., Marcora, S. M., & Coutts, A. J. (2015). Mental fatigue impairs intermittent running performance. *Medicine and Science in Sports and Exercise*, *47*(8), 1682.

Smith, M. R., Marcora, S. M., & Coutts, A. J. (2015). Mental Fatigue Impairs Intermittent Running Performance. *Medicine and Science in Sports and Exercise*, *47*(8), 1682.

Smith, M. R., Thompson, C., Marcora, S. M., Skorski, S., Meyer, T., & Coutts, A. J. (2018). Mental fatigue and soccer: Current knowledge and future directions. *Sports Medicine*, 1-8.

Smith, M. R., Zeuwts, L., Lenoir, M., Hens, N., De Jong, L. M., & Coutts, A. J. (2016). Mental fatigue impairs soccer-specific decision-making skill. *Journal of Sports Sciences*, *34*(14), 1297-1304.

Thompson, C. J., Fransen, J., Skorski, S., Smith, M. R., Meyer, T., Barrett, S., & Coutts, A. J. (2018). Mental fatigue in football: is it time to shift the goalposts? An evaluation of the current methodology. *Sports Medicine*, 1-7.

Van Cutsem, J., Marcora, S., De Pauw, K., Bailey, S., Meeusen, R., & Roelands, B. (2017). The effects of mental fatigue on physical performance: a systematic review. *Sports Medicine*, *47*(8), 1569-1588.

Verbruggen, F., & Logan, G. D. (2008). After-effects of goal shifting and response inhibition: A comparison of the stop-change and dual-task paradigms. *The Quarterly Journal of Experimental Psychology*, *61*(8), 1151-1159.

Vestberg, T., Gustafson, R., Maurex, L., Ingvar, M., & Petrovic, P. (2012). Executive functions predict the success of top-soccer players. *PloS one*, *7*(4), e34731.

Wesensten, N. J., G. Belenky, D. R. Thorne, M. A. Kautz and T. J. Balkin (2004). "Modafinil vs. caffeine: effects on fatigue during sleep deprivation." Aviation, Space, and Environmental Medicine 75(6): 520-525.

6 – WHAT ARE THE REAL-LIFE CAUSATIONS OF MENTAL FATIGUE IN PROFESSIONAL FOOTBALL?

6.1 – Rationale

In the current mental fatigue literature, it was recommended in chapter 4 that more ecologically valid protocols are developed to induce mental fatigue in applied football settings. The findings in chapter 5 strengthened this claim by suggesting that the modified Stroop task may not be an appropriate task to induce mental fatigue in dynamic tasks based on its low contextual interference (and subsequent inability to impact on congruent and incongruent reaction times) and significant impact on subjective boredom. It is also worth noting that in the current football literature, the participants recruited have consisted of junior Australian National Premier League players (Badin et al., 2016), Belgian national or provincial (division 2 - 7) players (Smith, Fransen 2017, Smith, Zeuwts, 2016; Smith, Coutts, et al., 2016), regional level youth players (Coutinho et al., 2018; Coutinho et al., 2017) and recreational players (Smith, Coutts, et al., 2016). These findings necessitate the need to further investigate the real-life cognitive tasks experienced by professional football players. Understanding this will allow for greater ecological validity in cognitive tasks employed in mental fatigue research. Thus, the aim of the following study was to use an online survey to query cognitive tasks completed and their subsequent impact on fatigue in English Football League and National League players.

6.2 - Understanding the cognitive demands experienced by professional soccer players: A perspective of English Football League and National League players.

The following section contains the following manuscript under review with the European Journal of Sport Science:

Understanding the cognitive demands experienced by professional soccer players: A perspective of English Football League and National League players.

The citations and references contained herein apply to this manuscript only and are formatted to the requirements of Science and Medicine in Football. The citations relate to the reference list within this section only and not to the reference list included at the end of this thesis.

Original title: Understanding the cognitive demands experienced by professional soccer players: A perspective of English Football League and National League players.

Running title: Mental fatigue in professional soccer.

Chris J Thompson [1, 2], Chris Towlson [3], John Perry [4], Aaron J Coutts [2], Mark Noon [5], Liam D Harper [6], Sabrina Skorski [1], Mitchell R Smith [7], Steve Barrett [8] & Tim Meyer [1].

1. Institute of Sports and Preventive Medicine, Saarland University, Saarbrücken, Germany.

2. Sport and Exercise Discipline Group, Faculty of Health, University of Technology Sydney, Moore Park, Australia.

3. Department of Sport, Health and Exercise Science, University of Hull, Kingston upon Hull, UK

4. Mary Immaculate College, Limerick, Ireland.

5. Faculty of Health and Life Sciences, Coventry University, Coventry, UK.

6. School of Human and Health Sciences, University of Huddersfield, Huddersfield, UK.

7. Exercise and Sports Science, Faculty of Science, University of Newcastle, Ourimbah, NSW, Australia

8. Sports Medicine and Science Department, Hull City FC, Kingston upon Hull, UK.

Corresponding author

Chris Thompson

Telephone - +49 (0) 681 302 70413 **Email -** chris.thompson@uni.saarland.de

Author ORCID

Chris Thompson: 0000-0001-5333-3616

Chris Towlson: 0000-0001-5960-0324

Sabrina Skorski: 0000-0001-8449-6872

Aaron Coutts: 0000-0002-1782-7691

Liam Harper: 0000-0002-2089-4799

Mitchell Smith: 0000-0002-8168-5405

Tim Meyer: 0000-0003-3425-4546

Word count - 4235

Abstract

Research investigating the impact of induced mental fatigue in soccer has demonstrated impairments in physical, skill and tactical performance in soccer-specific tasks and small-sided-games. Limitations of the research are the low ecological validity of the tasks used to induce mental fatigue and the lack of research investigating professional players. To inform the development of more ecologically valid methods of inducing mental fatigue in soccer, the aim of the current study was to investigate the real-life cognitive tasks performed pre-match and the presence of mental fatigue during training weeks and when exposed to match-play in professional soccer settings. First team male squad players (n = 167) from the 2nd to 5th tier of professional English soccer (English Football League (EFL) and National League (NL)) completed an online survey querying the prevalence of subjective mental fatigue from travel, media, pre-match activity, match-play and fixture congestion. Results showed there was a moderate prevalence of subjective mental fatigue at full-time (55 arbitrary units (AU), 0 – 100 scale), 24-hours post-match (45 AU), and for frequent bouts of match-play (39 AU) and travel (42 AU) in congested fixture periods. There was a minimal prevalence of subjective mental fatigue following exposure to acute tasks in-season, including team meetings (28 AU), travel to training (23 AU), and media commitments (19 AU). The results demonstrate that match-play and frequent bouts of travel have the greatest impact on mental fatigue in professional soccer. This study provides directions for future research in developing ecologically valid methods to induce mental fatigue.

Introduction

In association football (soccer) research, the physical demands of match-play are well understood, with varying physical performance levels being dependent on playing standard and playing position [1-3], and decrements in physical performance reported at various stages of a match caused by physiological mechanisms of fatigue [4]. The risk of physical fatigue may be increased when matches are played in congested schedules, with some professional players exposed to over sixty matches per season [5]. Aside from the impact of neuromuscular/metabolic fatigue commonly researched in professional soccer [6], a further consideration is the impact of mental fatigue. Indeed, fatigue is a complex term, and post-match fatigue in soccer has been related to several different factors including dehydration, glycogen depletion, muscle damage, and mental fatigue [7]. Further work elaborated on the risk of mental fatigue in soccer by discussing the high technical and tactical demands of match-play (i.e. frequent decision-making, adhering to team tactics and reacting to multiple external stimuli) and the frequent pressure to meet internal (i.e. manager, players, staff) and external (i.e. media, supporters) expectations in professional environments [8-9]. Mental fatigue is a psychobiological state experienced following exposure to cognitively demanding tasks [10-11] and has been demonstrated to negatively impact on endurance (running, cycling) performance [12]. However, relatively limited evidence is presently available in soccer.

Several studies have investigated the impact of induced mental fatigue on soccer-specific performance [13-18]. Negative effects of mental fatigue were reported in three laboratory studies which measured soccer-specific passing (Loughborough Soccer Passing Test) and shooting (Loughborough Soccer Shooting Test) performance [13-14] and visual search behaviour in a soccer-specific decision-making task [15]. In subsequent work measuring the impact of mental fatigue on small-sided-game performance, *unclear* effects of induced mental fatigue were found for physical performance (distance covered per minute and the number of accelerations and decelerations) [16], whilst *likely negative* effects were reported for technical (match involvement, match possession, tackle success) performance [17], and significant reductions in tactical performance (team synchronisation) [18].

Despite novel findings, a limitation of these studies is the use of low ecologically valid tasks to induce mental fatigue. For instance, five of the six aforementioned studies induced mental fatigue using a 30-min modified Stroop task [13-15, 17-18]. The modified Stroop task is a response inhibition/sustained attention task, and the most commonly used method of inducing mental fatigue [12]. The remaining study that examined mental fatigue in soccer [16] induced mental fatigue by incorporating a 20-min whole-body coordination task (juggling a tennis ball whilst completing agility ladders) which required motor coordination, sustained attention, cognitive processing and perceptual skills. Indeed, these mentally fatiguing tasks may not resemble the more varied and complex cognitive demands experienced by professional soccer players. During match-play, players are exposed to frequent bouts of decision-making in relation to the actions of their team-mates and opposition, whilst contending with external factors such as playing surface, crowd interaction and ambient light available during the match [8]. Players must consequently seek solutions to situations that involve varying and interacting constraints greater than the present methods of inducing mental fatigue [19]. Therefore, despite the response inhibition/sustained attention demands of the modified Stroop task, the limit in response variation and irrelevance to soccer-specific demands requires the investigation of real-life causes of mental fatigue in soccer.

To date, no known studies have examined the impact of mental fatigue on professional players. The subjects in the present mental fatigue in soccer literature were Australian National Premier League players [17], Belgian national or provincial (Division 2 - 7) players [13, 15], regional level youth players [16, 18] and recreational players [14]. Research has shown that elite athletes are less prone to sport-specific performance decrements following exposure to mentally fatiguing tasks. It has been demonstrated that the physical performance of professional cyclists was unaffected by a mentally fatiguing task (30-min Stroop task) when compared to non-professional cyclists [20]. Despite these results, the exact cause/presence of mental fatigue in professional soccer is yet to be investigated.

It is therefore necessary to understand the daily lifestyle and soccer-specific tasks performed by professional soccer players and the prevalence of mental fatigue. Gathering valuable information from a professional demographic will aid practitioners in soccer to identify risk factors for mental fatigue and allow future studies to use mentally fatiguing tasks with greater ecological validity. Therefore, the purpose of this study is to explore professional soccer players´ daily activity profiles during a training week (travel, team meetings, media commitments), pre-match activities of players, and perceptions of mental fatigue prior to, during and acutely post-match, plus the impact of fixture congestion.

Methods

Participants

Professional male soccer players (n = 167) voluntarily completed an online survey from July – December 2018. The sample consisted of first team squad players from the English Championship (n = 49), League One (n = 37), League Two (n = 50), and the National League (n = 31), which represent the second–fifth tiers of professional English soccer, respectively. The players varied in age (16 to 20 = 33 (19.8%), 21 to 25 = 79 (47.3%), 26 to 30 = 30 (18%), 31 to 35 = 19 (11.4%), 36 or over = 6 (3.6%)), position (goalkeeper = 21 (12.6%); full back = 28 (16.8%) central defender = 36 (21.6%); central midfielder = 36 (21.6%); wide midfielder = 17 (10.2%); striker = 29 (17.4%)) and years of professional playing experience (0 to 5 years = 89 (53%), 6 – 10 years = 46 (27.5%), 11 – 15 years = 18 (10.8%), more than 15 years = 14 (8.4%)). Ethical approval was obtained by the host institution under the Declaration of Helsinki.

Procedure

An initial survey containing 38 items was created by the lead researcher using an online electronic platform (Survey Monkey, California, USA). This was developed with the aid of three practitioners working in professional soccer, two researchers specialised in survey design and a mental fatigue researcher. The survey was piloted with 38 professional and 61 semi-professional soccer players, who were instructed to provide verbal feedback on the relevance and clarity of the questions provided. Following discussions with survey respondents and members of the research team, several questions were deleted (due to survey length and perceived irrelevance and repetition of questions) and replaced with new questions, several questions were rephrased, and clear definitions were subsequently included where deemed appropriate. The revised survey comprised of 34 items and was separated into six sections. Section 1 ("*Participant information and perceptions of mental and physical fatigue*", 6 items), consisted of questions related to age, playing position, playing standard and experience, plus a checklist of words and phrases which players selected as perceived definitions of mental and physical fatigue. In Section 2 ("*Travel*", 4 items), the modality of transport used to reach the club training facilities, the length and frequency of these journeys and the perceived cognitive demand of travel was queried. Section 3 ("*Tactical information and media commitments*", 6 items) focused on frequency, duration and perceived cognitive demand of team meetings and media engagements. Section 4 ("*Pre-match activity*", 8 items) questioned the activity engagement of players two hours prior to kick-off, the use of caffeine, and the duration and perceived cognitive demand of the pre-match team talk. Section 5 ("*Match-play*", 5 items) consisted of statements related to the cognitive demands of several match-play scenarios, whilst Section 6 ("*Fixture congestion*", 5 items) also used statements based on the perceived cognitive demands of congested fixture periods, repeated bouts of travel, enthusiasm to play in matches and the idea of a winter break in English soccer. The survey consisted of multiple-choice responses, checkboxes to select more than one answer where appropriate, blinded (for opinion based questions) and unblinded (for duration based questions) 0-100 arbitrary unit (AU) scales and empty text boxes to give the opportunity for respondents to provide further information if required.

Survey completion

Survey invitations were sent via email to practitioners from 116 English soccer clubs (20 Premier League, 72 Football League and 24 National League). Enclosed was a participation information sheet outlining the background and rationale for the study, a PDF of the survey questions for non-playing staff to read, and an online link to the survey for players to complete. Subsequent reminder emails were sent to clubs who had not replied within 28 days of the original invitation. The average completion time of the survey was 8 minutes 16 seconds.

Statistical analysis

Preliminary screening identified missing data, problematic outliers, and assessed univariate normality for scaled variables. The main analyses examined each section of the survey in turn. Initially, words used to describe physical and mental fatigue (section 1) were explored relative to demographic information using chi-square. Section 2 of the survey (travel) included both nominal and scaled variables. Nominal variables were assessed according to demographic information using chi-square, while scaled variables were assessed using a one-way ANOVA with planned pairwise comparisons for position, age, playing experience, and division. Section 3 (team meetings and media commitments) included some ordinal variables, which were examined using a Kruskal-Wallis test, and scaled variables were subjected to a similar one-way ANOVA as described above. Section 4 (pre-match activity) nominal variables were assessed using chi-square while the scaled variables were assessed using a one-way ANOVA. Similar ANOVAs with planned pairwise comparisons were conducted for all variables in section 5 (match-play) and section 6 (fixture congestion).

The large quantity of data obtained required multiple comparisons. To correct for the likelihood of type one errors resulting from this, we calculated the False Discovery Rate (FDR) recommended by Benjamini and Hochberg [21]. This method calculates a q value that p must be lower than to not be deemed a false discovery. We also conducted 2000 bootstrapped samples of all analyses and the null hypothesis was rejected if and only if $p < q$ and, for scaled variables, the 95% confidence interval did not contain zero. Magnitude of effect was interpreted using Ferguson's recommendations for minimum practical effect [22].

Results

Descriptions of physical and mental fatigue

Table 1 presents the frequency of selection for each descriptor for physical fatigue and mental fatigue. Generally, mental fatigue was considered much more broadly than physical fatigue, which is illustrated by the relative similarity of word size in Figure 1.

Table 1.

Physical fatigue and mental fatigue descriptors indicated by participants with chi-square values.

*$p < q$

Descriptor	Physical (%)	Mental (%)	χ^2	*p*
Difficulty in reacting to mistakes	15	44.9	6.34	0.012*
Reduced motivation	18.6	51.5	4.02	0.045
Tense	9	18	.85	0.357
Exhausted	68.9	42.5	4.26	0.039
A difficulty in maintaining concentration	27	56.9	5.08	0.024*
Reduced reaction times	41.3	43.7	6.17	0.013*
Feeling sleepy drowsy	28.7	31.7	12.87	<0.001*
Reduced arousal	9	14.4	13.97	<0.001*
On edge	3.6	19.2	.81	0.369
Sluggish	61.7	37.1	4.96	0.026*
Pain soreness	41.9	7.2	5.81	0.016*
Angry	6.6	25.8	19.36	<0.001*
Reduced energy levels	77.8	35.9	.79	0.373
Confusion	1.2	19.8	1.17	0.280
Weak	39.5	20.4	17.24	<0.001*
Slow	52.7	30.5	14.02	<0.001*
Panicky	1.2	21.6	7.37	0.007*
A difficulty in maintaining performance levels	37.1	41.3	31.97	<0.001*

A **B**

Figure 1. Selected descriptors of physical fatigue (A) and mental fatigue (B) with size representative of frequency.

Travel to training

Most (97.6%) of participants travel to training by car. The majority of these indicated that they drive (77.2%), with the remainder in a carpool (17.4%), or a passenger (3.0%). Only three participants (1.8%) walked to training and only one (0.6%) cycled. The players rated mental fatigue from travelling ("My journey to training is mentally fatiguing") at just 23 on a scale of 0-100 AU (0 – never, 100 - always). Unsurprisingly, the length of a journey was positively correlated with how tiring participants perceived their journey to be (r = .61, p < .001, 95% CI = .50, .70). There was however, no divisional effects on perceived mental fatigue of journey to training (F(3,163) = .69, p = .56). Further, there was no substantive effect on perceived mental fatigue of journey to training for age (F(4,162) = 2.30, p = 0.06) or playing experience (F(3, 163) = .33, p = .80).

Team meetings

Team meetings took place on average twice per week with a mean duration of 26 minutes. There were no significant differences in frequency of team meetings for age, playing experience, or position. The frequency of team meetings was positively related to length of team meetings (r = .27, p < .001, 95% CI = .13, .41). The players rated mental fatigue from team meetings ("I find team meetings mentally fatiguing") at 28 on a scale of 0-100 AU (0 – never, 100 - always). Both the frequency (r = .29, p < .001, 95% CI = .14, .42) and the length (r = .37, p < .001, 95% CI = .23, .50) were significantly positively associated with perceived mental fatigue from team meetings. There was no age, playing experience, or position effects on length of team meetings or perceived fatigue from team meetings.

Media commitments

Overall, 44.9% of participants spoke to the media once every few months, 25.2% indicated that they spoke to the media once a month, 15.6% stated once a fortnight, 2.4% stated every week, and just three (1.8%) indicated that they spoke to the media more than once a week. Almost 1 in 10 (9.6%) stated that they never communicated with the media. The average length of a media commitment was 14 minutes. This was different between divisions ($F(3,147) = 4.34$, $p < 0.01$), and playing experience ($F(3,147) = 3.13$, $p < 0.05$). Specifically, the length of media commitments for those in the Championship ($M_{diff} = 6.52$, $p < q$, $d = .74$) and in League One ($M_{diff} = 5.37$, $p < q$, $d = .87$) were greater than in the National League. Moreover, there were no mental fatigue effects for division, age, playing experience, or position. On average, participants rated mental fatigue from speaking with the media at just 19 AU (0 – never, 100 - always).

Pre-match

Pre-match activity

In the two hours prior to kick-off, the most commonly cited activity was listening to music (77%). Many players also noted communicating with friends or family (54%), discussing team tactics with teammates or coaching staff (50%), and using social media (43%). Just under a third (29.94%) completed psychological techniques, 27% completed superstitious rituals, 26% watched videos, and 21% played card games.

Caffeine consumption

A majority (71.9%) of the sample indicated that they consumed caffeine before a match. This was significantly related to age ($p < q$, $V = .36$) and playing experience ($p < q$, $V = .32$). Indeed, ≥ 90% of those aged over 25 consumed caffeine before a match, while 69.6% of 21-25 and only 45.5% 16-20 year old players used caffeinated products.

Team talk

On average, players indicated that they received a team talk approximately 18 minutes before a match. This was not significantly affected by division ($F(3,116) = 1.55$, $p = .21$). However, the length of the team talk was significantly ($F(3/116) = 5.02$, $p < .01$) shorter in the Championship than in League Two ($M_{diff} = -2.30$, $p < q$, 95% CI = -3.79, -.81) and in the National League ($M_{diff} = -3.01$, $p < q$, 95% CI = -4.83, -1.19). Players rated mental fatigue from listening to a pre-match team talk at just 11 AU (0 –

never, 100 - always). There was no significant correlation between the length of time before kick-off a team talk took place and the perceived mental fatigue from the team talk (r = .05, p = .58, 95% CI = -.13, .29).

Match-play

We reflectively explored perceptions of mental fatigue immediately prior to, during, and after a match with a series of questions requiring a response from 0 to 100 AU (0 – never, 100 - always), as presented in Table 2. There was a statistically significant effect for time (F(2.62, 387.75) = 49.50, p < 0.001), as mental fatigue increased significantly (all $p < q$) at each time point until full-time, before declining 24-hours post-match. However, there were no statistically significant interaction effects with division or age and time.

Table 2.

Descriptive statistics (mean±SD) for perceptions of mental fatigue immediately prior to, during, and after a match by division (0 - 100 AU, scale: never - always).

	Championship (n = 49)	League One (n = 37)	League Two (n = 50)	National League (n = 31)	(n
Mental fatigue 5 minutes before kick-off	22.6 (22.3)	22.7 (24.5)	19.36 (20.8)	17.4 (18.5)	20.7
Mental fatigue at half-time	30 (18)	30 (18.9)	29.6 (20.2)	32 (16)	30.
Mental fatigue at full-time	55.3 (25.7)	51.7 (23.5)	57 (26.6)	57.5 (15.9)	55.
Mental fatigue 24 hours after a match	41.5 (27.8)	49.7 (24.1)	42.1 (26.4)	48.6 (25)	44.8
Negative impact of mental fatigue on match	40.5 (27.2)	47.5 (23.90)	37.6 (26.6)	41.7 (25.2)	41
Top class opposition more mentally fatiguing	30 (21.8)	42.3 (22.3)	42 (30.1)	48 (27.4)	39.7

Fixture congestion

Table 3 displays questions pertained to the influence of fixture congestion on mental fatigue. Despite only a moderate perceived cognitive demand of congested match-play (39±23 AU) and frequent travel demands (42±21 AU), players supported a winter break (70±28 AU). Following FDR corrections, there were no effects for division, playing experience, or position. However, there were some age-related effects. Specifically, players aged 16-20 reported the match scheduling as significantly (F(4,162) = 4.29, p < .01) less mentally fatiguing than players aged 21-25 (M_{diff} = -12.67, $p < q$, 95% CI = -21.71, -3.64, d = .54), 26-30 (M_{diff} = -15.19, $p < q$, 95% CI = -26.19, -4.19, d = .78), and 31-35 (M_{diff} = -25.05, $p < q$, 95% CI = -37.61, -12.50, d = 1.28). Further, there was a significant decline in match enthusiasm with age (F(4,162) = 3.42, p = .01). Following corrections for FDR ($p < q$), the only statistically significant finding in this category was the difference (d = 1.05) in enthusiasm between 16-20 year old participants (73 AU) and participants aged 31-35 (45 AU).

Table 3.

Descriptive statistics (mean ±SD) for total responses to questions pertaining to fixture congestion (0 – 100 AU, strongly disagree – strongly agree)

	Mean ± SD
"The regular travel commitments are mentally fatiguing"	42±21
"The frequent match scheduling is mentally fatiguing"	39±23
"I enter each match with the same enthusiasm"	61±29
"I sometimes become bored of frequently playing football matches"	21±25
"A winter break is beneficial for maintaining performance levels throughout the whole season"	70±28

Discussion

The present study aimed to identify the real-life cognitive demands experienced by professional football players (travel, team meetings, media), pre-match activity (player activity, team talks), as well as the prevalence of mental fatigue throughout match-play, post-match and during congested fixture periods. The results showed that tasks performed by professional soccer players (both pre-match and during a regular training week) do not elicit the cognitive engagement/complexity to the same extent demonstrated (predominantly via the modified Stroop task) in previous literature [13-18]. These findings show that players do not enter matches with high levels of mental fatigued. Moreover, subjective mental fatigue increases at the end of match-play and remains elevated 24-hours post-match. The travel demands associated with fixture congestion also appear to elicit mental fatigue for some players, and most professional players support the idea of a winter break. Overall, these findings suggest that the prevalence of mental fatigue in soccer has been overestimated in previous literature [9].

A primary aim of the current study was to establish the tasks completed by players in the lead up to a match. In the two hour period before kick-off, music and communication with teammates/staff were the most common pastimes, which did not induce subjective mental fatigue. Music has been shown to increase arousal, facilitate task-relevant imagery and improve motor task performance in sport-specific physical and cognitive activities [23-24]. Further research [25] demonstrated that compared to a control condition (i.e. quiet room), music played in a warm-up period prior to physical activity (resistance training) reduces post-activity rating of perceived exertion (RPE) and cardiovascular responses (heart rate and blood pressure). Caffeine consumption pre-match was also prevalent amongst the current sample, which has been shown to enhance cognitive function and soccer-specific (Loughborough Soccer Passing Test) performance [26], plus reduce perceptions of mental fatigue [27]. Indeed, caution is advised with the interpretation of caffeine effectiveness, as chronic use can reduce improvements in reaction time and visual vigilance [28]. Overall, real-life tasks performed by professional soccer players pre-match are not cognitively complex or challenge to negatively impact on soccer-specific performance. These findings demonstrate that the current method of inducing mental fatigue immediately before a performance task [13-18] does not accurately represent the activities performed in a performance environment. Indeed, the aforementioned studies were experimental models, and the current findings may lead to more accurate representations (i.e. choice of mentally fatiguing task) of mental fatigue in soccer research.

Our study also showed that professional football players predominantly experience feelings of mental fatigue at the end of match-play. Similar findings were reported in a study of an English Premier League club, which reported an elevated perceived technical/cognitive exertion 15-30 min post-match, with significantly greater ratings when playing against top 6 teams (when compared to bottom 6 teams) [29]. Whilst the current study has demonstrated elevated subjective mental fatigue post-match, a limitation of the survey was not further identifying time points (i.e 60 – 75-min, 76 – 90 min) in which the onset of perceived mental fatigue occurred. However, it must be acknowledged that this is difficult for respondents to accurately recall and quantify.

The immediate post-match perception of mental fatigue suggests that this feeling may have also been experienced at the latter stages of a match. Previously research has demonstrated that the lowest high intensity running values are evident in the final 15 min of a match [30], and the greatest number of goals are scored in the final 15 min period [31]. Moreover, match-specific fatigue has been shown to impair technical performance of elite Serie A players (Rampinini et al., 2008 [32] and short-passing ability in young soccer players (Rampinini et al., 2009) [33]. Indeed, performance decrements could be partly explained by mental fatigue, which when using non-sport-specific tasks in laboratory settings has impaired attention [34], reaction times [10], plus the monitoring of performance and slower adjustments in performance after errors [11]. To understand the onset of mental fatigue in soccer, further research is required using soccer-specific mentally fatiguing tasks (i.e. 90-min match-play) and quick and simple to administer measures of mental fatigue (e.g. VAS) in regular time intervals (i.e. during brief pre-determined pauses in a match).

A further aim of the survey was to investigate the cognitive demands experienced by players throughout a typical in-season week to identify risk factors for mental fatigue. A low prevalence of mental fatigue was evident for players exposed to media demands and team meetings, as well as the frequent journeys to training sessions. These findings are explained by their brief duration (media commitment – 14 minutes; team meeting - 26 minutes; journey to training – 38 minutes) in relation to previous research which induced mental fatigue via prolonged listening and driving. In a prolonged listening study, exposure to a 50 min auditory choice task (i.e. responding to audible cues using a keypad) resulted in a significant increase in mental fatigue and significant decreases in arousal, motivation and response time/accuracy measures [35]. Similarly, despite previous research detailing the impact of 90 – 120-min driving protocols on subjective and objective mental fatigue [36-37], the lower journey duration (38-min) and low perceived feeling of mental fatigue (23 AU) demonstrates this duration of travel does not generally induce mental fatigue. A car journey to training sessions may also be accompanied by music, which can have a positive impact on arousal and driving performance [38]. Therefore, everyday cognitive tasks performed by professional soccer players are acute in nature, performed frequently in a weekly routine and do not meet the duration or complexity to elicit mental fatigue.

Overall, the present study has revealed lifestyle and soccer-specific tasks completed by professional players and prevalence of mental fatigue resulting from travel, training and match-play. These findings provide alternative tasks with greater ecologically validity to induce mental fatigue in future research, thus replacing non-soccer-specific tasks used in previous experimental models [13-18]. Further work is also required to determine the time-point in which mental fatigue should be induced in research studies, as professional players surveyed in the current study report that they do not enter matches in a mentally fatigued state. As mental fatigue is not reported in the pre-match or half-time period in the current study, mental fatigue in soccer-specific contexts (i.e. match-play) could be induced in the middle or later phases of a future study's performance task to match the subjective demands of professional players from the current study. A limitation of the current study was the survey focussing primarily on acute mental fatigue, meaning chronic mental fatigue definitions necessitates future research. The impact of season-long campaigns, international call-ups and accumulative training and travel loads are just a few real-life scenarios which may elicit mental fatigue. Moreover, other professional demographics such as academy and female players must also be considered in future work. Indeed, academy and female settings are typically accompanied by other cognitive demands (i.e. combining full-time soccer with education/work commitments) which are not typically experienced by professional male players.

Conclusion

The present study sought to investigate common lifestyle and soccer-specific tasks amongst English Football League and National League players with relation to perceptions of mental fatigue. Feelings of mental fatigue were reported to be prevalent at the end of a match, and remained elevated 24-hours post-match. Overall it was found that many cognitive tasks (i.e. pre-match and training days) are performed routinely in short periods, with little perceived presence of mental fatigue. This is likely due to the complexity and duration of the tasks, which are significantly lower than tasks that have been used in experimental mental fatigue research. Despite the current findings, individual differences are likely evident between players and stages of the season, and practitioners are advised to monitor this fluctuation using such protocols as including mental fatigue in wellness questionnaires or via regular communication with players. Future research is also required to address additional factors relevant to soccer in different playing demographics.

Compliance with Ethical Standards

Funding - No sources of funding were used to assist in the preparation of this article.

Conflict of interest - Chris J. Thompson, Chris Towlson, John Perry, Aaron J. Coutts, Mark Noon, Liam Harper, Sabrina Skorski, Mitchell R. Smith, Steve Barrett & Tim Meyer declare that they have no conflicts of interest relevant to the content of this article.

References

1. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. J Sport Sci. 2003;21:519-28.

2. Bloomfield J, Polman R, O'Donoghue P. Physical demands of different positions in FA Premier League soccer. J Sports Sci Med. 2007;6:63.

3. Di Salvo V, Baron R, Tschan H, Montero FC, Bachl N, Pigozzi F. Performance characteristics according to playing position in elite soccer. Int. J. Sports Med. 2007;28:222-7.

4. Mohr M, Krustrup P, Bangsbo J. Fatigue in soccer: a brief review. Journal of sports sciences. 2005 Jun 1;23(6):593-9.Carling C, McCall A, Le Gall F, Dupont G. What is the extent of exposure to periods of match congestion in professional soccer players? J Sport Sci. 2015;33:2116-24.

5. Carling C, McCall A, Le Gall F, Dupont G. What is the extent of exposure to periods of match congestion in professional soccer players?. J Sport Sci. 2015 Dec 14;33(20):2116-24.

6. Bangsbo J, Iaia FM, Krustrup P. Metabolic Response and Fatigue in Soccer. Int J Sports Physiol Perform. 2007;2:111-27.

7. Nédélec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. Recovery in soccer. Sports Med. 2012 Dec 1;42(12):997-1015.

8. Thompson CJ, Fransen J, Skorski S, Smith MR, Meyer T, Barrett S, Coutts AJ. Mental Fatigue in Football: Is it Time to Shift the Goalposts? An Evaluation of the Current Methodology. Sports Med. 2018;2:1-7.

9. Coutts AJ. Fatigue in football: it's not a brainless task!. J Sport Sci. 2016 Jul;34(14):1296.

10. Boksem M, Meijman T, Lorist M. Effects of mental fatigue on attention: an ERP study. Brain Res Cogn Brain Res. 2005;25:107–16. https://doi.org/10.1016/j.cogbr ainres.2005.04.011.

11. Lorist M, Boksem M, Ridderinkhof K. Impaired cognitive control and reduced cingulate activity during mental fatigue. Brain Res Cogn Brain Res. 2005;24:199–205. https://doi.org/10.1016/j.cogbrainres.2005.01.018.

12. Van Cutsem J, Marcora S, De Pauw K, Bailey S, Meeusen R, Roelands B. The effects of mental fatigue on physical performance: a systematic review. Sports Med. 2017 Aug 1;47(8):1569-88.

13. Smith M, Fransen J, Deprez D, Lenoir M, Coutts AJ. Impact of mental fatigue on speed and accuracy components of soccer- specific skills. Sci Med Footb. 2017;1:48–52. https://doi.org/10.1080/02640414.2016.1252850.

14. Smith M, Coutts A, Merlini M, Deprez D, Lenoir M, Marcora SM. Mental fatigue impairs soccer-specific physical and technical performance. Med Sci Sports Exerc. 2016;48:267–76. https://doi.org/10.1249/MSS.0000000000000762.

15. Smith M, Zeuwts L, Lenoir M, Hens N, De Jong LMS, Coutts AJ. Mental fatigue impairs soccer-specific decision making skill. J Sports Sci. 2016;34:1297–304. https://doi.org/10.1080/02640414.2016.1156241.

16. Coutinho D, Gonçalves B, Travassos B, Wong DP, Coutts AJ, Sampaio JE. Mental fatigue and spatial references impair soccer players' physical and tactical performances. Front Psychol. 2017;21(8):1645. https://doi.org/10.3389/fpsyg.2017.01645.

17. Badin O, Smith M, Conte D, Coutts AJ. Mental fatigue: impairment of technical performance in small-sided soccer games. Int J Sports Physiol Perform. 2016;11:1100–5. https://doi.org/10.1123/ijspp.2015-0710.

18. Coutinho D, Gonçalves B, Wong D, Travassos B, Coutts AJ, Sampaio J. Exploring the effects of mental and muscular fatigue in soccer players' performance. Hum Mov Sci. 2018;58:287–96.

19. Phillips E, Davids K, Renshaw I, Portus M. Expert performance in sport and the dynamics of talent development. Sports Med. 2010 Apr 1;40(4):271-83.

20. Martin K, Staiano W, Menaspà P, Hennessey T, Marcora S, Keegan R. Superior Inhibitory Control and Resistance to Mental Fatigue in Professional Road Cyclists. PLoS ONE. 2016;11(7):e0159907.

21. Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the Royal statistical society: series B (Methodological). 1995 Jan;57(1):289-300.

22. Ferguson CJ. An effect size primer: a guide for clinicians and researchers. Professional psychology: Research and Practice. 2009 Oct;40(5):532.

23. Bishop DT, Wright MJ, Karageorghis CI. Tempo and intensity of pre-task music modulate neural activity during reactive task performance. Psychol Music. 2014;42:714-27.

24. Pain MA, Harwood C, Anderson R. Pre-competition imagery and music: The impact on flow and performance in competitive soccer. Sport Psychol. 2011;25:212-32.

25. Arazi H, Asadi A, Purabed M. Physiological and Psychophysical Responses to Listening to Music during Warm-Up and Circuit-Type Resistance Exercise in Strength Trained Men. J Sports Med. 2015;24:2.

26. Foskett A, Ali A, Gant N. Caffeine enhances cognitive function and skill performance during simulated soccer activity. Int J Sport Nutr Exerc Metab. 2009;19:410-23.

27. Azevedo R, Silva-Cavalcante MD, Gualano B, Lima-Silva AE, Bertuzzi R. Effects of caffeine ingestion on endurance performance in mentally fatigued individuals. Eur J Appl Physiol. 2016;116:2293-303.

28. Judelson DA, Armstrong LE, Sökmen B, Roti MW, Casa DJ, Kellogg MD. Effect of chronic caffeine intake on choice reaction time, mood, and visual vigilance. Physiology & Behavior. 2005 Aug 7;85(5):629-34.

29. Barrett S, McLaren S, Spears I, Ward P, Weston M. The influence of playing position and contextual factors on soccer players' match differential ratings of perceived exertion: a preliminary investigation. Sports. 2018;6:13.

30. Bangsbo, J., & Mohr, M.. Variations in running speed and recovery time after a sprint during top-class soccer matches. Med Sci Sports Exerc. 2005;37:87.

31. Abt, G. A., Dickson, G., & Mummery, W. K. (2002). Goal scoring patterns over the course of a match: an analysis of the Australian national soccer league. In Spinks, W., Reilly, T. y Murphy, A. (Eds.). Science and Football IV (pp. 106-111). London: Routledge.

32. Rampinini E, Impellizzeri FM, Castagna C, Azzalin A, Ferrari DB, Wisløff UL. Effect of match-related fatigue on short-passing ability in young soccer players. Med Sci Sports Exerc. 2008 May;40(5):934-42.

33. Rampinini E, Impellizzeri FM, Castagna C, Coutts AJ, Wisløff U. Technical performance during soccer matches of the Italian Serie A league: Effect of fatigue and competitive level. J Sci Med Sport. 2009 Jan 1;12(1):227-33.

34. Chaudhuri A, Behan PO. Fatigue in neurological disorders. The Lancet. 2004 Mar 20;363(9413):978-88.

35. Moore TM, Key AP, Thelen A, Hornsby BW. Neural mechanisms of mental fatigue elicited by sustained auditory processing. Neuropsychologia. 2017 Nov;106:371-82.

36. Zhao C, Zhao M, Liu J, Zheng C. Electroencephalogram and electrocardiograph assessment of mental fatigue in a driving simulator. Accid Anal Prev. 2012;45:83–90.

37. Lal SK, Craig A. Driver fatigue: electroencephalography and psychological assessment. Psychophysiology. 2002;39:313–21.

38. Ünal AB, de Waard D, Epstude K, Steg L. Driving with music: Effects on arousal and performance. Transp Res Part F Traffic Psychol Behav. 2013;1:52-65.

7 – WHAT ARE THE REAL-LIFE CAUSATIONS OF MENTAL FATIGUE IN ELITE ACADEMY FOOTBALL?

7.1 – Rationale

Chapter 6 revealed a minimal prevalence of mental fatigue in elite senior male football when completing frequent and short duration tasks that were both football- and non-football specific. Whilst these findings are novel and provide practical applications to elite settings, other demographics in elite football may also be prone to mental fatigue. For instance, academy players likely face greater cognitive exposure than senior elite players as they must balance the demands of football with full time educational commitments. Indeed, playing experience and standard may also impact on susceptibility to mental fatigue, as shown in the differences in performance decrement in elite and recreational cyclists by Martin et al., (2015) when exposed to a mentally fatiguing task. Therefore, the aim of the following study was to investigate the cognitive demands experienced by elite English academy age players (U14 – U23) and subsequent perception of mental fatigue and performance.

7.2 - Understanding the presence of mental fatigue in English academy soccer players.

This section contains the following published manuscript:

Understanding the presence of mental fatigue in English academy soccer players.

The citations and references contained herein apply to this manuscript only and are formatted to the requirements of Journal of Sports Sciences. The citations relate to the reference list within this section only and not to the reference list included at the end of this thesis.

Understanding the presence of mental fatigue in English academy soccer players.

Chris J Thompson [1, 2], Mark Noon [3], Chris Towlson [4], John Perry [5], Aaron J Coutts [2], Liam D Harper [6], Sabrina Skorski [1], Mitchell R Smith [7], Steve Barrett [8] & Tim Meyer [1].

1. Institute of Sport and Preventive Medicine, Saarland University, Saarbrücken, Germany.

2. Sport and Exercise Discipline Group, Faculty of Health, University of Technology Sydney, Moore Park, Australia.

3. Faculty of Health and Life Sciences, Coventry University, Coventry, UK.

4. Department of Sport, Health and Exercise Science, University of Hull, Kingston upon Hull, UK.

5. Mary Immaculate College, Limerick, Ireland.

6. School of Human and Health Sciences, University of Huddersfield, Huddersfield, UK.

7. Exercise and Sports Science, Faculty of Science, University of Newcastle, Ourimbah, NSW, Australia.

8. Sports Medicine and Science Department, Hull City FC, Kingston upon Hull, UK.

Corresponding author

Chris Thompson

Telephone - +49 (0) 681 302 70413 **Email -** chris.thompson@uni.saarland.de

Word count – 4402.

Abstract

Research has demonstrated that induced mental fatigue impairs soccer-specific technical, tactical and physical performance in soccer players. The findings are limited by the lack of elite players and low ecological validity of the tasks used to induce mental fatigue, which do not resemble the cognitive demands of soccer. The current study collected survey data from English academy soccer players (n = 256; age groups - U14 – U23), with questions comprising of five themes (descriptors of physical and mental fatigue, travel, education, match-play and fixture congestion). The survey consisted of multiple choice responses, checkboxes and blinded/unblinded (for duration based questions) 0-100 arbitrary unit (AU) slider scales. Listening to music (81.6% of players), using social media (58.3%) and watching videos (34.3%) were the most common pre-match activities. Pre-match subjective mental fatigue was low (18.7±18.8 AU), and most frequently reported at the end of a match (47±26 AU) and remained elevated 24-hours post-match (36±27 AU). Travel (29±24 AU), fixture congestion (44±25 AU) and education (30±26 AU) demonstrated a low to moderate presence of subjective mental fatigue. These findings provide an overview of activities performed by English academy soccer players pre-match, and demonstrate that mental fatigue is experienced as a result of match-play.

Introduction

In elite academy soccer, physical loading (e.g. total running distance, high intensity running distances, number of sprints) placed on players during match-play incurs physical fatigue [1, 2]. Research investigating fatigue in soccer has predominately been measured from a neuromuscular and metabolic standpoint [3], although a further emerging topic is the role of mental fatigue [4]. Indeed, players frequently make quick and accurate decisions with reference to ball location and the actions of team-mates and opposing players, whilst influenced by physical, technical and tactical factors [5]. These processes require prolonged vigilance, decision making, constantly receiving and processing information, which have been theorised to contribute to mental fatigue during match-play [6]. Subsequent literature [7] proposed that non-soccer-specific factors (travel, screen exposure and lifestyle stressors) provide an increased risk of mental fatigue. However, the presence and impact of mental fatigue in soccer remains unknown for several reasons; 1) a lack of research in the area, 2) a lack of elite players recruited in the literature and 3) the low ecological validity of the tasks used to induce mental fatigue.

In the six original investigative articles assessing the impact of mental fatigue on physical, technical and tactical soccer performance (for a review, please consult Smith et al. 2018 [8]), participants were either recreational or sub-elite youth soccer players, which questions the presence of mental fatigue in highly skilled players. Previous research has demonstrated a difference in resilience to mental fatigue between competitive level. Following a 30-min incongruent Stroop task, elite cyclists displayed greater performance preservation in a 20-min cycling time trial test compared to recreational cyclists [9]. It is therefore possible that highly skilled soccer players are less prone to subjective mental fatigue than lower-skilled counterparts, although this remains unknown. Moreover, the cognitive tasks used to induce mental fatigue in soccer research have been questioned due to low ecological validity [7, 10]. To induce mental fatigue prior to a soccer-specific performance test, participants completed a 30-min computer or paper based version of the modified

Stroop task [11-15] or a 20-min whole-body motor coordination task (completing agility ladders whilst juggling a tennis ball) requiring motor coordination, sustained attention, cognitive processing and perceptual skills [16]. Although this research has identified the negative effects of mental fatigue on performance, such generic non-specific tasks fail to reflect the cognitive demands of soccer-specific actions, which consist of greater task complexity and variability under pressure. More specifically, the low contextual interference of the modified Stroop task (i.e. repetitive activity) does not represent the high contextual inference (i.e. unpredictable activity with greater variation in task demand) of soccer [7]. As recently stated by Carling et al [10], it is therefore essential to determine the extent to which mental fatigue occurs in soccer players by developing mentally fatiguing tasks with high ecological validity.

Understanding the real-life cognitive activities performed by highly skilled soccer players and the subjective presence of mental fatigue can aid future research by developing mentally fatiguing protocols with greater ecological validity. This information will also allow practitioners to identify interventions to reduce the impact of mental fatigue on performance. Access to elite soccer environments for research purposes can be challenging due to time, identity exposure and equipment concerns, meaning a more simplistic anonymous approach must be considered. However, the use of online surveys was recently advocated [17] to bridge the gap between research and practice in sport science. Indeed, surveys are quick and easy to administer and can reach a large cohort with anonymity. Therefore, the purpose of this study is to implement an online survey for English academy soccer players which investigates the real-life cognitive activity exposure, and presence of subjective mental fatigue in soccer-specific (i.e. match-play), education, travel and lifestyle scenarios.

Methodology

Participants

The sample consisted of youth soccer players (n = 256) representing Category 1 & 2 (the two highest tiers of English academy soccer) teams in England. The players varied in age (U14 – 38 (14.8%); U15 – 15 (5.9%); U16 – 46 (18%); U17 – 15 (5.9%); U18 – 94 (36.7%); U19 – 14 (5.5%); U20 – 1 (0.4%); U21 – 1 (0.4%); U23 – 32 (12.5%)), position (goalkeeper = 31 (12.1%); full back = 44 (17.2%) central defender = 51 (19.9%); central midfielder = 63 (24.6%); winger = 39 (15.2%); striker = 28 (10.9%)) and period of time contracted to a professional academy system (0 – 3 years = 90 (35.2%); 4 – 6 years = 65 (25.4%); 7 – 9 years = 73 (28.5%); 10 years or more = 28 (10.9%)). Ethical approval was obtained by the host institution under the Declaration of Helsinki.

Procedure

An invitation email was sent to practitioners connected to academy clubs in the English Premier League (n = 20) and Football League (n = 72). Recipients were informed that the survey was investigating the perceived presence of mental fatigue in academy soccer, would take no longer than 10-min to complete, and could be conducted on a laptop, a tablet device or mobile phone. Subsequent reminder emails were sent to practitioners if there was no response to the initial contact after 28 days.

Survey design

An initial survey containing 32 items was created using an online platform (Survey Monkey, California, USA). The initial survey was piloted with 19 elite and 64 regional academy soccer players. Verbal and written feedback was obtained from respondents based on the clarity and relevance of the questions used. Based on this feedback and further discussions with the research team, a revised 29 item survey consisting of five sections was created. Section 1 (*"Participant information and perceptions of mental and physical fatigue"* - 5 items) collected baseline information related to age category, playing experience and playing position. This section also contained two opinion-based questions which asked players to select from a list of words (e.g. “a difficulty in maintaining performance levels”, “reduced reaction times”, “reduced motivation”) which they would associate with the terms “physical fatigue” and ”mental fatigue”. In Section 2 (“Travel” - 4 items), the modality, frequency and duration of journeys to training were queried, along with the perceived presence of mental fatigue from the journeys. The education commitments and perceived influence of education on soccer commitments were explored in Section 3 (“Education“ - 4 items), whilst Section 4 (“Pre-match activity and match-play” - 12 items) examined activity profiles of players in the final two hours prior to kick off and perceived subjective mental fatigue of travelling to away matches, pre-match team talks and match-play. Section 5 (“Fixture congestion” - 4 items) investigated the frequency of academy match-play and the perceived cognitive demand of playing in congested schedules. The survey consisted of multiple choice responses, checkboxes to select more than one answer where appropriate, blinded (for opinion based questions) and unblinded (for duration based questions) 0-100 arbitrary unit (0-100) slider scales and empty text boxes to provide the opportunity for respondents to provide further information if required.

Statistical analysis

Survey data were initially screened for missing data and outliers. Univariate skewness and kurtosis were also examined. Each section of the survey was then analysed sequentially. Firstly, words used to describe physical and mental fatigue in section 1 (*Participant information and perceptions of mental and physical fatigue*) were explored relative to demographic information using chi-square. This section also included both nominal and scale variables. Nominal variables were assessed relative to demographic information examining chi-square. Scale variables from section 2 (*Travel*) were examined using a one-way ANOVA with planned pairwise comparisons for position, age, playing experience, and division. In section 3 (*Education*), ordinal variables were examined using a Kruskal-Wallis test, while scale variables were subjected to a similar one-way ANOVA as described above. Section 4 (*Pre-match activity and match-play*) contained nominal and scale variables.

Nominal variables were assessed using chi-square, while scale variables were examined using a one-way ANOVA. As section 5 (*Fixture congestion*) contained only scale variables, ANOVAs with planned pairwise comparisons were conducted.

In total, there were significant multiple comparisons and therefore it was necessary to correct for these to reduce the likelihood of a type one error. To correct for this, we calculated the False Discovery Rate (FDR) recommended by Benjamini and Hochberg [18]. This method requires the calculation of a q value that must be greater than p to not be deemed a false discovery. All analyses were subjected to 2000 bootstrapped samples and the null hypothesis was rejected if and only if $p < q$ and, for scale variables, the 95% confidence interval did not contain zero. Effect sizes were interpreted using Ferguson's recommendations for minimum practical effect [19]. Specifically, strength of association (e.g., Cramer's V for chi-square) indices were practically significant when $V \geq .20$ and group differences (e.g., Cohen's d for pairwise comparisons) were considered to be of practically significant when $d \geq .41$.

Results

Descriptions of physical and mental fatigue

There were clear distinctions in how participants described perceptions of physical fatigue and mental fatigue. The most prominent descriptors of physical fatigue were "Exhausted" (72%), "Reduced energy levels" (62.7%), and "Sluggish" (55.2%). For mental fatigue, the most common descriptors were "A difficulty in maintaining concentration" (55%), "Reduced motivation" (43.5%), and "Difficulty in reacting to mistakes" (37.3%). Chi-square (χ^2) associations in Table 1 represent the extent to which individuals identify the descriptor as being only related to physical fatigue or mental fatigue. Overall, physical fatigue was largely associated with energy, while mental fatigue was associated with cognition.

Descriptor	Physical (%)	Mental (%)	χ^2	*p*	Cramer's *V*
"Difficulty in reacting to mistakes"	18.5	37.3	.59	.444	.05
"Reduced motivation"	21	43.5	3.45	.063	.11
"Tense"	13.3	16.2	1.09	.296	.06
"Exhausted"	72	30.3	3.12	.078	.11
"Angry"	10.3	30.7	12.11	.001*	.21
"A difficulty in maintaining concentration"	25.1	55	12.62	<.001*	.22
"Reduced reaction times"	32.8	34.7	3.75	.053	.12
"Feeling sleepy/drowsy"	38	32.8	16.35	<.001*	.25
"Reduced arousal"	6.3	15.5	9.13	.003*	.18
"On edge"	5.2	18.1	15.21	<.001*	.24
"Sluggish"	55.4	21.8	.90	.32	.06
"Pain soreness"	51.3	5.2	.01	.921	.01
"Reduced energy levels"	62.7	21.4	.62	.423	.05
"Confusion"	6.6	32.5	10.28	.001*	.20
"Weak"	39.1	14	13.21	<.001*	.22
"Panicky"	3.3	25.1	13.75	<.001*	.23
"A difficulty in maintaining performance levels"	32.1	21.4	15.42	<.001*	.24

*$p < q$

Table 1.

Physical fatigue and mental fatigue descriptors indicated by participants with chi-square values.

Travel

86% of participants travelled to training by car, primarily as a passenger (59%). While only 22 participants (8.8%) noted that they used public transport to travel to training; they all represented the U15 & U19 squads. This contributed to a significant age group effect on mode of travel (χ^2 = 194.15, p < .001, V = .35). Unsurprisingly, a significant variation in the frequency of training sessions for different age groups was found (F(8,259) = 43.65, $p < q$). As illustrated in Figure 1, U20 to U23 players trained at least five times per week. Three training sessions per week was most common for U14 to U16 players.

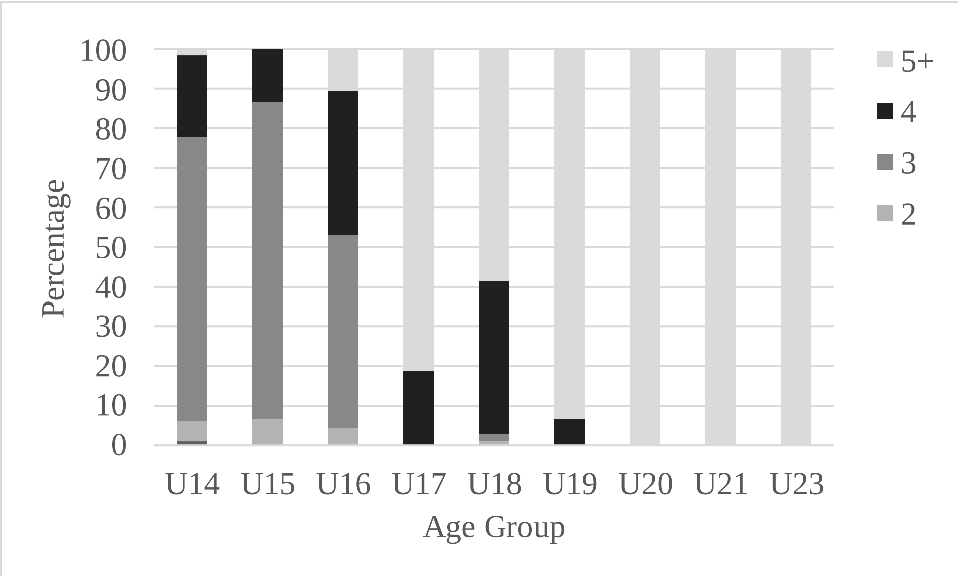


Figure 1.

Self-report frequency of training per week by age group.

The average length of the journey to training was 32.±18.7-min. Participants rated the subjective mental fatigue related to their average journey to training at 29±25 AU (0 – never, 100 - always). This was not significantly impacted by age group ($F(8,262) = 1.66$, $p = .11$). The correlation between journey length and journey fatigue was small to moderate ($r = .36$, 95% CI = .35, .46, $p < .001$).

Education

All U17 players were in full-time education, and all but two of the 98 U18s were also in education. However, of those in the U19 and U23 age groups, only 36.5% were currently in education. Less than 1 in 10 (7.7%) of participants from age groups U19 and upwards were in higher education. As education is compulsory up to 16, days in education were close to 5 per week for such groups. This was substantively fewer however for U17 ($M_{\text{hours per week}}$ = 8.6±3), U18 ($M_{\text{hours per week}}$ = 9.1±3.1), U19 ($M_{\text{hours per week}}$ = 6±4.7), and U23 players ($M_{\text{hours per week}}$ = 5.1±4.3). There was a low positive correlation between hours in education and the mental aspects of education (i.e. classroom lessons, coursework, exam preparation) having a perceived negative impact on soccer-specific performance ($r = .27$, $p < .001$, 95% CI = .15, .39). A similar association existed between hours in education and physical aspects of education (i.e. physical education and extracurricular sport) having a perceived negative impact on soccer-specific performance ($r = .24$, $p < .001$, 95% CI = .11, .36). However, the negative perceived impacts were largely contained to U14 players (M_{mental} = 49±33 AU, all other ages $M < 33$ AU; M_{physical} = 40±28 AU, all other ages $M \leq 21$ AU). Overall, there was a clear trend that the mental aspects of education had a greater negative effect on performance than physical aspects (Mdiff = 8.9, $t(230) = 5.05$, $p < .001$).

Pre-match activity

Listening to music was the most commonly cited activity players engaged in during the final two hours prior to kick-off on a match day (81.6%). Over half (58.3%) reported using social media in this time. Around one-third (34.3%) of participants indicated that they watched videos, 21.4% slept, 12.6% prayed, 12.2% played mobile app games, 8.5% played video games, 7% played card games/puzzles, and 2.2% of players reported reading before games.

Travelling to away matches

Three modes of transport for away matches were identified by participants; travelling on a team bus (67.9%), passenger in a car (29.4%), and driving (2.7%). There was a significant effect for age (χ^2 = 53.72, p < .001, V = .45), as younger participants were more reliant upon being driven to away matches. For age groups U19 and above, travel was almost exclusively on the team bus. The majority (79.1%) of participants indicated that they reached the match location between 1-2 hours prior to kick-off. Overall, the journey to an away match (Q18 - "The journey to an away match is mentally fatiguing") was considered somewhat mentally fatiguing (39±24 AU; 0 – never, 100 - always). The age group affected most by travel was the U14s (45±31 AU). Overall, there was a moderately strong positive correlation between the perception of how fatiguing the journey was and that the journey had a negative impact on performance (r = .64, p < .001, 95% CI = .56, .71).

Match-play

Perceptions of mental fatigue on match day are presented in Table 2. The average length of a pre-match team talk was 10±4.8-min and occurred, on average, 32±17.3-min prior to kick off. Listening to a team-talk had a low perceived subjective impact on mental fatigue (11±18 AU). Five minutes prior to kick off, subjective mental fatigue was greater, though still not substantial (19±19 AU). Subjective mental fatigue at half-time was greater still (32±20 AU), but peaked immediately after the match (47±26 AU). This was affected by age (F(6,249) = 4.21, p < q), where it was significantly higher in the U19s than the U15s and U16s, and significantly higher in the U18s than in the U16s. Subjective perceptions of mental fatigue reduced only moderately 24 hours post-match (36±27 AU), and was unaffected by age group.

Mental fatigue indicator	Under 14s (*n* = 38)	Under 15s (*n* = 15)	Under 16s (*n* = 48)	Under 17s (*n* = 15)	Under 18s (*n* = 96)	Under 19s (*n* = 15)	Under 23s (*n* = 36)
Journey to away match	49±28	31±21	32±20[a]	36±20	38±25	37±13	43±20
From team talk	30±32	6±7[a]	5±8[a]	5±8[a]	9±14[a]	6±6[a]	8±10[a]
5-min before kick-off	28±26	9±13[a]	15±17[a]	12±16	20±19	14±10	20±16
At half-time	33±25	17±16	27±20	38±18	32±19	35±16	38±15[b]
Immediately after match	43±29	31±25	37±27	55±25	53±25[c]	61±27[b,c]	51±20
24 hours after match	37±35	31±23	29±25	30±22	36±26	44±29	43±27

Table 2. Mean and SD (0-100 AU) of mental fatigue indicators on match day by age group.

[a]Statistically significantly different (p < q) from under 14s, [b]under 15s, [c]under 16s.

Match congestion

36.2% of participants played soccer in addition to their academy club commitments. This was significantly affected by age group (χ^2 = 70.99, *p* < .001, *V* = .51). The proportion who played away from the academy by age was 48.7% (U14s), 73.33% (U15s), 76% (U16s), 12.5% (U17s), 16.2%

(U18s), 20% (U19s), and 24.3% (U23s). Age groups up to and including U16s were typically also involved in school soccer (66.4%). Participation in other additional soccer activities was minimal. Three players indicated that they played Sunday League soccer (1.1%), four (1.5%) played 5-a-side, nine (3.3%) played county soccer, and nine (3.3%) played internationally.

On average, participants played 1.5±0.8 matches per week. This varied significantly by age group (F(6,249) = 2.57, $p < q$). While there was a general trend that the younger participants played more frequently, post-hoc analyses corrected for multiple corrections did not specify any statistically significant comparisons. The frequency of matches was not related to responses for the item "It is mentally fatiguing to frequently play in competitive soccer matches" (r = -.00, p = .99, 95% CI = -.12, .12). The response to this item was 44±25 AU on the 0-100 scale (0 – strongly disagree, 100 – strongly agree) and was not significantly affected by age group (F(6,249) = 1.70, $p > q$). The frequency of competitive matches was also not significantly related to perceptions of boredom (r = .06, p = .35, 95% CI = -.07, .18). In response to the item "I become bored of frequently playing competitive soccer matches", players typically scored this very low (i.e., strongly disagree; 11±17 AU). This did depend somewhat on age group (F(6,249) = 3.16, $p < q$), as U14s players scored statistically significantly higher than those in the U18s age group (M_{diff} = 13.45, SE = 3.18, $p < q$, 95% CI = 3.69, 23.21). Indeed, the U14s scored higher on perceived boredom than all groups, though these were not statistically significant after correcting for multiple comparisons. There was a small positive relationship between mental fatigue from frequency of competitive matches and boredom (r = .23, p < .001, 95% CI = .11, .34).

Discussion

The present study aimed to identify the real-life cognitive demands experienced by English academy soccer players in non-soccer specific activities (travel, education), pre-match activities (player activity, team talks), and the presence of mental fatigue throughout match-play, post-match and during congested fixture periods. The results showed that tasks performed by English academy soccer players (both pre-match and during a regular training week) do not elicit the cognitive engagement/complexity demonstrated (predominantly via the modified Stroop task) in previous literature [11-16]. These findings determine that players do not enter matches mentally fatigued, but subjective perceptions of mental fatigue increase throughout match-play and remains elevated 24-hours post-match. Other factors (travel, education, intake of tactical information) generally did not incur subjective mental fatigue. Whilst the current findings demonstrate that the presence of mental fatigue in soccer has been overestimated in previous literature [6], differences are likely to occur in other elite settings (i.e. adult elite players), who face different commitments and pressures to win.

The first section of the survey determined the association English academy soccer players made with the terms “physical fatigue” and “mental fatigue”. Indeed, mental fatigue is a novel and complex phenomenon, and participants may be unable to accurately define the meaning of the term [7]. In the current study, players selected phrases (“a difficulty in maintaining concentration”, “reduced motivation”, and “difficulty in reacting to mistakes”) which resonated with the impact of induced mental fatigue reported in the literature. More specifically, mental fatigue impairs attention [20], reaction times [21], performance monitoring and slower adjustments in performance after errors [22]. In recent research [23], focus groups with 32 athletes and coaches in professional sport identified several descriptors of mental fatigue (disengagement, decreased motivation and enthusiasm, increased displays of emotion and withdrawal, changes in concentration, decreased discipline and attention to detail) similar to the findings of the current study. These findings show that athletes can distinguish between physical fatigue and mental fatigue, demonstrating a competency in the understanding of mental fatigue. The ability for players to define mental fatigue could aid practitioners in detecting fluctuations in mental fatigue and identifying interventions to reduce its impact.

One of the other main objectives of the current study was to establish common activities performed in the two hour period of preparation before a match. Understanding this time window is important due to the present use of tasks with low ecological validity to induce mental fatigue in soccer research [7]. The results showed that screen-based activities (using social media, watching videos (e.g. YouTube/Netflix), playing mobile app games and playing video games) were prevalent before a match. Previous research investigating screen based activities have provided contrasting results. Firstly, a 30-min smartphone puzzle application ("Brain it on") impaired Yo-Yo Intermittent Recovery Test level 1 and Loughborough Soccer Passing Test performance in academy soccer players (compared to a resting control group) [24]. Whilst an improvement in ecological validity compared to previous research, the nature of the task (complex puzzles) likely provides a greater cognitive demand than the more prevalent use of social media, videos and games in the current cohort. Conversely, in a university student population, mental fatigue (measured by pre to post change in mathematical task performance) was unaffected by video game participation (FIFA 15, Electronic Arts) [25]. This study was limited by a failure to include a control group or report the number of games played/duration of games. Along with screen based activities, listening to music proved to be a popular choice of activity pre-match. Music has proven effective in increasing motor task performance, emotional regulation and arousal for sport-specific physical and cognitive activities [26-27]. Based on the low perceived subjective feeling of mental fatigue 5-min before kick-off, music likely has a positive impact on arousal and motivation, and despite the prevalent use of screen time activity, it did not provide a cognitive demand great enough to induce mental fatigue. Contrary to previous research which induced mental fatigue before a soccer-specific activity [11-16] the pre-match time period does not appear to be a prevalent time-point for the occurrence of mental fatigue in English academy soccer players.

Following the limited presence of subjective mental fatigue following pre-match activity, it is necessary to discuss other time periods which may induce mental fatigue. English academy soccer players in the current study are exposed to frequent travel commitments (i.e. travel to training and matches) and intake of tactical information (i.e. team talks) from coaching staff. However, these activities were not perceived to induce mental fatigue. This may be explained by their duration (10-min) and complexity of information received. Previous literature [28] has demonstrated that prolonged auditory processing (50-min auditory processing task) impaired cognitive task performance, decreased arousal and motivation, and increased mental fatigue. Exposure to cognitively demanding speech-picture verification tasks of contrasting difficulty levels in different signal-to-noise ratios (SNRs) has also been shown to increase pupil diameter, denoting a reduction in physiological arousal [29]. However in real-life soccer scenarios, a pre-match team talk likely contains a summary of themes previously discussed and prepared for in training, providing little novel complex information and therefore minimal cognitive demand. A low perceived presence of mental fatigue from travel to training may be explained by a shorter mean duration of travel time (32-min) compared to previous studies (90-120-min) which have demonstrated mental fatigue through monotonous simulated road travel [30-31]. Travel duration to away matches proved difficult to implement in the pilot survey due to such a high variation in journeys throughout a season and difficulty in recalling the information, meaning it was removed from the final survey. Therefore despite a minimal presence of mental fatigue when travelling to away matches, this perception is likely open to fluctuation based on the location of the club and frequency of long travel durations. Future research could monitor travel fatigue experienced on long monotonous coach journeys to understand the impact of varying travel distances.

The current study also demonstrated a minimal impact of fixture congestion on perceived mental fatigue. This is the first known study to investigate this, as previous fixture congestion research has focused on physical performance decrements [32-35]. These findings may be explained by the lack of exposure to congested fixture periods (mean number of games per week = 1.5±0.8). The low prevalence of congested periods at academy level may provide a difficulty in players providing an educated and experienced response to such questions, in comparison to senior elite players who can be exposed to more than sixty games per season [36]. Education commitments (physical and mental) were also shown to have minimal perceived impact on soccer-specific performance. Combining education and sport can be challenging, as shown by research which cited schedule clashes and fatigue as limiting factors to sporting performance [37] and a perceived cause of mental fatigue [23]. The contrast in findings can be explained for several reasons. Firstly, elite academy soccer players may be given a clear distinction between time committed to soccer and education, with special dispensation for exam and coursework deadlines based on soccer commitments, therefore minimising the stress of education. Conversely, the current survey may have lacked enough depth in questioning to elucidate the impact of education on performance. The timing of questioning can also have an impact on response. The survey was completed between July – December, a time traditionally free of exams and demanding coursework deadlines in the UK. It is recommended that future research frequently administers a survey throughout a season to understand fluctuations in responses.

Conclusion

This study provides novel findings which demonstrates English academy soccer players' understanding of mental fatigue and perceptions of mental fatigue when exposed to tasks cited as potentially detrimental to performance in previous work (Thompson et al. 2018; Coutts, 2016). The results show that mental fatigue is not prevalent at pre-match, nor in several other soccer-specific scenarios, but is subjectively present post-match and 24-hours post-match. These findings provide a reference point for subsequent research which incorporates ecologically valid protocols in mental fatigue studies. Such studies could include the impact of relevant screen time exposure (social media/watching videos) on soccer-specific performance, or the impact of music on the alleviation of mental fatigue. Travel is potentially more problematic for players based on team location, and future surveys could factor for this by splitting cohorts into geographical regions of the country. Additionally, the timing of future surveys must also be considered. Indeed, certain themes in the survey are likely to fluctuate in the season, such as the impact of education on soccer-specific performance (during exam periods) or fixture congestion (during a tournament phase), and future survey designs must be conducted frequently with comparisons made to early, mid and late phases of the season.

Disclosure of interest

The authors report no conflict of interest.

References

1. Rampinini E, Bosio A, Ferraresi I, Petruolo A, Morelli A, Sassi A. Match-related fatigue in soccer players. Medicine & Science in Sports & Exercise. 2011 Nov 1;43(11):2161-70.
2. Mohr M, Krustrup P, Bangsbo J. Fatigue in soccer: a brief review. J Sport Sci. 2005 Jun 1;23(6):593-9.
3. Bangsbo J, Iaia FM, Krustrup P. Metabolic Response and Fatigue in Soccer. Int J Sports Physiol Perform. 2007;2:111-27.
4. Nédélec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. Recovery in soccer. Sports Med. 2012 Dec 1;42(12):997-1015.
5. Williams AM. Perceptual skill in soccer: implications for talent identification and development. J Sports Sci. 2000;18(9):737–50.
6. Coutts AJ. Fatigue in football: it's not a brainless task!. J Sport Sci. 2016 Jul;34(14):1296

7. Thompson CJ, Fransen J, Skorski S, Smith MR, Meyer T, Barrett S, Coutts AJ. Mental Fatigue in Football: Is it Time to Shift the Goalposts? An Evaluation of the Current Methodology. Sports Med. 2018;2:1-7.
8. Smith MR, Thompson C, Marcora SM, Skorski S, Meyer T, Coutts AJ. Mental fatigue and soccer: current knowledge and future directions. Sports Medicine. 2018 Jul 1;48(7):1525-32.
9. Martin K, Staiano W, Menaspà P, Hennessey T, Marcora S, Keegan R, Thompson KG, Martin D, Halson S, Rattray B. Superior inhibitory control and resistance to mental fatigue in professional road cyclists. PloS one. 2016 Jul 21;11(7):e0159907.
10. Carling C, Lacome M, McCall A, Dupont G, Le Gall F, Simpson B, Buchheit M. Monitoring of Post-match Fatigue in Professional Soccer: Welcome to the Real World. Sports Medicine. 2018 May 8:1-8.
11. Smith M, Fransen J, Deprez D, Lenoir M, Coutts AJ. Impact of mental fatigue on speed and accuracy components of soccer- specific skills. Sci Med Footb. 2017;1:48–52. https://doi.org/10.1080/02640414.2016.1252850.
12. Smith M, Coutts A, Merlini M, Deprez D, Lenoir M, Marcora SM. Mental fatigue impairs soccer-specific physical and technical performance. Med Sci Sports Exerc. 2016;48:267–76. https://doi.org/10.1249/MSS.0000000000000762.
13. Smith M, Zeuwts L, Lenoir M, Hens N, De Jong LMS, Coutts AJ. Mental fatigue impairs soccer-specific decision making skill. J Sports Sci. 2016;34:1297–304. https://doi.org/10.1080/02640414.2016.1156241.
14. Badin O, Smith M, Conte D, Coutts AJ. Mental fatigue: impairment of technical performance in small-sided soccer games. Int J Sports Physiol Perform. 2016;11:1100–5. https://doi.org/10.1123/ijspp.2015-0710.
15. Coutinho D, Gonçalves B, Wong D, Travassos B, Coutts AJ, Sampaio J. Exploring the effects of mental and muscular fatigue in soccer players’ performance. Hum Mov Sci. 2018;58:287–96.

16. Coutinho D, Gonçalves B, Travassos B, Wong DP, Coutts AJ, Sampaio JE. Mental fatigue and spatial references impair soccer players' physical and tactical performances. Front Psychol. 2017;21(8):1645. https://doi.org/10.3389/fpsyg.2017.01645.
17. Harper LD, McCunn R. 'Hand in Glove': using qualitative methods to connect research and practice. Int J Sports Physiol Perform. 2017;12(7):990-3.
18. Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the Royal statistical society: series B (Methodological). 1995 Jan;57(1):289-300.
19. Ferguson CJ. An effect size primer: a guide for clinicians and researchers. Professional psychology: Research and Practice. 2009 Oct;40(5):532.
20. Chaudhuri A, Behan PO. Fatigue in neurological disorders. The lancet. 2004 Mar 20;363(9413):978-88.
21. Boksem M, Meijman T, Lorist M. Effects of mental fatigue on attention: an ERP study. Brain Res Cogn Brain Res. 2005;25:107–16. https://doi.org/10.1016/j.cogbr ainres.2005.04.011.
22. Lorist M, Boksem M, Ridderinkhof K. Impaired cognitive control and reduced cingulate activity during mental fatigue. Brain Res Cogn Brain Res. 2005;24:199–205. https://doi.org/10.1016/j.cogbrainres.2005.01.018.
23. Russell S, Jenkins D, Rynne S, Halson SL, Kelly V. What is mental fatigue in elite sport? Perceptions from athletes and staff. European Journal of Sport Science. 2019 May 13:1-26.
24. Greco G, Tambolini R, Ambruosi P, Fischetti F. Negative effects of smartphone use on physical and technical performance of young footballers. Journal of Physical Education and Sport. 2017 Dec 1;17(4):2495-501.
25. Aliyari H, Kazemi M, Tekieh E, Salehi M, Sahraei H, Daliri MR, et al. The effects of FIFA 2015 computer games on changes in cognitive, hormonal and brain waves functions of young men volunteers. Basic Clin Neurosci. 2015;6:193.

26. Bishop DT, Wright MJ, Karageorghis CI. Tempo and intensity of pre-task music modulate neural activity during reactive task performance. Psychol Music. 2014;42:714-27.
27. Pain MA, Harwood C, Anderson R. Pre-competition imagery and music: The impact on flow and performance in competitive soccer. Sport Psychol. 2011;25:212-32.
28. Moore TM, Key AP, Thelen A, Hornsby BW. Neural mechanisms of mental fatigue elicited by sustained auditory processing. Neuropsychologia. 2017 Nov;106:371-82.
29. McGarrigle R, Dawes P, Stewart AJ, Kuchinsky SE, Munro KJ. Pupillometry reveals changes in physiological arousal during a sustained listening task. Psychophysiology. 2017 Feb;54(2):193-203.
30. Zhao C, Zhao M, Liu J, Zheng C. Electroencephalogram and electrocardiograph assessment of mental fatigue in a driving simulator. Accid Anal Prev. 2012;45:83–90.
31. Lal SK, Craig A. Driver fatigue: electroencephalography and psychological assessment. Psychophysiology. 2002;39:313–21.
32. Carling C, McCall A, Le Gall F, Dupont G. The impact of short periods of match congestion on injury risk and patterns in an elite football club. Br J Sports Med. 2016 Jun 1;50(12):764-8.
33. Bengtsson H, Ekstrand J, Hägglund M. Muscle injury rates in professional football increase with fixture congestion: an 11-year follow-up of the UEFA Champions League injury study. Br J Sports Med. 2013 Aug 1;47(12):743-7.
34. Dellal A, Lago-Peñas C, Rey E, et al. The effects of a congested fixture period on physical performance, technical activity and injury rate during matches in a professional soccer team. Br J Sports Med. 2013. doi: 10.1136/bjsports-2012-091290.PubMedGoogle Scholar
35. Dupont G, Nedelec M, McCall A, McCormack D, Berthoin S, Wisløff U. Effect of 2 soccer matches in a week on physical performance and injury rate. The American journal of sports medicine. 2010 Sep;38(9):1752-8.

36. Carling, C., Gregson, W., McCall, A., Moreira, A., Wong, D. P., & Bradley, P. S. (2015). Match running performance during fixture congestion in elite soccer: research issues and future directions. *Sports Medicine*, *45*(5), 605-613.
37. Cosh S, Tully PJ. Stressors, coping, and support mechanisms for student athletes combining elite sport and tertiary education: Implications for practice. The Sport Psychologist. 2015 Jun;29(2):120-33.

8 – WHAT ARE THE REAL-LIFE CAUSATIONS OF MENTAL FATIGUE IN ELITE FEMALE FOOTBALL?

8.1 – Rationale

Following chapter 6, chapter 7 provided revealed a low prevalence of mental fatigue in common football specific activities, and also educational commitments in youth footballers. The football and lifestyle specific tasks in question were typically frequent and short duration. Another elite demographic potentially prone to mental fatigue is elite female players representing both domestic and international teams. Indeed, international football alone is conversely associated with infrequent gatherings and longer duration tasks, such as greater travel demands. Further potential stressors include a condensed period of tactical preparation, fixture congestion and internal and external pressures to succeed. An additional challenge in a female demographic is balancing international commitments not only with domestic football scheduling, but often with education and/or employment commitments. The aim of the following study was to use focus groups to understand the psychological demands (driven by anecdotal and research-based claims) experienced in elite female football.

8.2 - Understanding the presence of mental fatigue in elite female football

The following section contains the following manuscript under review with Qualitative Research in Sport, Exercise and Health:

Understanding the presence of mental fatigue in elite female football.

The citations and references contained herein apply to this manuscript only and are formatted to the requirements of the International Qualitative Research in Sport, Exercise and Health. The citations relate to the reference list within this section only and not to the reference list included at the end of this thesis.

Understanding the presence of mental fatigue in elite female football.

Chris J Thompson[a,b*], Andy Smith[c], Aaron J Coutts[b], Sabrina Skorski[a], Naomi Datson[d], Mitchell R Smith[e], & Tim Meyer[a].

[a]Institute of Sport and Preventive Medicine, Saarland University, Saarbrücken, Germany; [b]Sport and Exercise Discipline Group, Faculty of Health, University of Technology Sydney, Moore Park, Australia; [c]Department of Sport and Physical Activity, Edge Hill University, Ormskirk, UK; [d]Institute of Sport, University of Chichester, Chichester, UK; [e]Exercise and Sports Science, Faculty of Science, University of Newcastle, Ourimbah, NSW, Australia.

Corresponding author - Chris Thompson

Telephone - +49 (0) 681 302 70413 **Email -** chris.thompson@uni.saarland.de

Andy Smith: smithand@edgehill.ac.uk Twitter - @ProfAndySmith

Aaron Coutts: aaron.coutts@uts.edu.au Twitter - @AaronJCoutts

Sabrina Skorski: s.skorski@mx.uni-saarland.de Twitter - @Brina1812

Naomi Datson: n.datson@chi.ac.uk Twitter - @NaomiDatson

Mitchell Smith: mitch.smith@newcastle.edu.au Twitter - @Mitch_R_Smith

Tim Meyer: tim.meyer@mx.uni-saarland.de Twitter - @TimMeye85834325

Author ORCID

Chris Thompson: 0000-0001-5333-3616

Andy Smith: 0000-0001-9801-3982

Aaron Coutts: 0000-0002-1782-7691

Sabrina Skorski: 0000-0001-8449-6872

Mitchell Smith: 0000-0002-8168-5405

Tim Meyer: 0000-0003-3425-4546

Word count - 6801

Abstract

Previous research investigating the impact of induced mental fatigue on football (soccer) performance has demonstrated associated performance decrements in physical, technical, tactical and decision-making performance. A common limitation amongst these articles is the protocols used to induce mental fatigue which provide low ecological validity, and the inclusion of recreational or sub-elite players. Understanding the presence of mental fatigue in elite football can provide insight into protocols with greater ecological validity. The current study used focus group interviews with 10 elite female football players, focusing on five topics (travel, fixture congestion, receiving tactical information, pre-match routine and pressure to win) related to the perceived causes mental fatigue in elite football (directed by anecdotal quotes in elite football and research-based theories). Several themes emerged from the data; travel fatigue, inability to switch off from football, fatigue experienced following team meetings, use of pre-match music and internal pressure to succeed. These findings present practical recommendations to reduce mental fatigue in elite football settings, and ecologically valid mentally fatiguing protocols for future research. Coaches are advised to consider the timing, content and duration of team meetings, provide players with free time/rest where possible, and consider modality of coaching instructions during matches.

Keywords

Female football, mental fatigue.

Introduction

In elite female football (soccer), the physical demands of match-play (i.e. total distance run, volume of high-intensity running, number of sprints) are well understood (Datson et al., 2017; Bradley et al., 2010), however the mental demands remain unknown, and are limited to editorials, which are considered a low level of evidence. Bauman (2016) theorises the monetary pressure, pressure to perform, plus the influence of the multiple media outlets that are quick to glorify successful athletes and critical to those who fail. Coutts (2016) has also speculated that mental fatigue is present in elite football, but this has yet to be assessed empirically. Mental fatigue is a psychobiological state, characterised by feelings of tiredness and a lack of energy, and is induced by prolonged periods of demanding cognitive activity (Boksem, Meijman, and Lorist 2005, Lorist, Boksem, and Ridderinkhof 2005). Mental fatigue is suggested by Coutts (2016) to be experienced by elite football players from pressures received from coaching staff, supporters, the media and club sponsors. Players are also likely exposed to mental fatigue during matches, due to the requirement to remain vigilant and adapt to opposition movements and to the match tactics of their own coach (Coutts 2016). Such decisions must be made quickly and accurately under high levels of pressure in a dynamic environment (Williams 2000). At present however, the evidence detailing the presence of mental fatigue in elite female football is limited by the lack of female representation in the literature.

Only six original studies have examined the effect of mental fatigue on football-specific performance (see Smith et al., 2018 for a review); all of which have been conducted using recreational or sub-elite academy age male players. Three of these were laboratory investigations which reported impaired football-specific skill performance (Loughborough Soccer Shooting Test and Loughborough Soccer Passing Test) (Smith et al., 2017, Smith, Coutts et al., 2016) and visual search behaviour in a football-specific decision making task (Smith, Zeuwts et al., 2016). In small-sided-games, mental fatigue has had unclear effects on physical (distance covered per minute and the number of accelerations and decelerations) performance (Coutinho et al., 2017), negative effects for technical (match involvement, match possession, tackle success) performance (Badin et al., 2016), along with reductions in tactical performance due to decreased team dispersion and movement synchronisation (Coutinho et al., 2018). Indeed, these findings may not resemble the demands experienced by elite female football players, who are under-represented in psychological research (Gledhill, Harwood and Forsdyke, 2017). Bensing et al., (1999) describe a psychological framework hypothesising a contrast in how males and females cope with physical symptoms, emotions and stress, and that there may even be a difference in personality structure. Future research is required to understand the psychological demands experienced in elite female football and its impact on performance. Moreover, it is of interest to understand the real-life causations of mental fatigue, as the current tasks used to induce mental fatigue provide little ecological validity in football-specific settings (Thompson et al., 2018; Carling et al., 2018). The aforementioned studies have used either a 30-min modified Stroop task (Coutinho et al., 2018; Smith et al., 2017; Badin et al., 2016; Smith, Coutts et al., 2016; Smith, Zeuwts et al., 2016b) or a 20-min whole-body coordination task (juggling a tennis ball whilst completing agility ladders) (Coutinho et al., 2017) to induce mental fatigue. These tasks do not resemble the real-life cognitive activities experienced by football players, and as stated by Carling et al., (2018), it is important for future mental fatigue research to develop ecologically valid protocols to induce mental fatigue in football-specific environments.

Without an understanding of the real-life causations of mental fatigue in football, and no representation of female players in the literature, the aim of the current study is to use focus groups with elite female football players to explore the presence of mental fatigue and impact on performance. Indeed, elite female football players must balance domestic (and potentially international) training/match-play demands with full time/educational commitments, leaving less time for a break in comparison to elite male counterparts (e.g. off-season, winter break, recovery days in-season). It is expected that the findings from this study will guide practitioners in understanding causations of mental fatigue and how to minimise its presence, as well as develop mentally fatiguing protocols with greater ecological validity.

Methods

Participants

Ten elite female football players (age – 27.1 ± 4.8 y) were recruited for the study. All players represented the same international team (collective number of senior international appearances - 411), and were contracted to domestic clubs in England, Scotland and Northern Ireland. The players were exposed to a full domestic season in their respective leagues (English Women's Soccer League – 18 matches; Scottish Women's Premier League – 21 matches; Northern Ireland Premier League – 18 matches), as well as several call-ups to international fixtures per season, both in and out of the domestic season period. Moreover, players all combined football with full-time education, employment (part-time and full-time), or a combination of the two.

Procedures

Following university ethical approval, permission was obtained by the head coach of an international female football team to recruit players from the squad to participate in the study. All players were informed of the purpose and aims of the study and were provided a guarantee of confidentiality throughout the process of conducting the focus groups.

Focus group procedure

Two focus groups (2 x 5 players) each lasting approximately sixty minutes were conducted to enable players to engage in an open discussion and share their opinions in a comfortable environment (Smith, Harré, and Van Langenhove 1995). As a guideline for the focus groups, a pre-prepared list of questions and phrases pertinent to the aims of the study was created. This approach was taken due to previous research which has demonstrated or theorised the impact of football-related actions (i.e. travel, prolonged listening, match-play, fixture congestion) on the presence of mental fatigue (Thompson et al., 2018; Smith et al., 2018; Coutts, 2016; Moore et al., 2017). Moreover, a news article related to the question was initially presented to the group before each question to facilitate discussion and help depersonalise the question and potential responses. Each article contained a quotation from a player, manager, practitioner or official related to their exposure to mental fatigue, and players in the focus group were then asked to provide their opinion on the article and discuss whether it related to their own experiences.

The focus groups consisted of an introductory phase and a list of five question topics with sub-questions. In the introductory phase, the lead researcher built a rapport with the group by speaking about themes related to football, explaining the nature of the focus group and providing a reassurance that any information gathered would remain confidential. The first topic explored the group's perception of travel demands ("How do you find having to travel frequently with your teams? What, if any, mental demand does this have on you? Can you give me any examples?"). Second, the relationship between fixture congestion and mental fatigue was examined ("I have here an article from an international football manager who speaks about the risk of mental fatigue in the lead up to tournaments, particularly from players playing in England without a winter break. What do you think about this?"). Third, the group's opinion about a magazine article which spoke of the potential "analysis paralysis" of receiving high amounts of tactical information from coaches was explored ("Do you have any experience of this? If so, can you describe what happened and how you felt?"). The fourth topic focused on the players' pre-match routine, beginning with an anecdotal account from a high profile retired football player's pre match routine, followed by the probing of the group's own routines ("What, if any, typical routines do you have on the day of a match before kick-off? Why do you do this? How, if at all, does it make you feel mentally?"). The final topic was examined using a quotation from a news article by a high profile football manager related to the mental pressure associated with match outcome success ("I have here an article from a manager who speaks about the huge pressure to win and how it may be more mentally – than physically – difficult to win matches. How would you describe the pressure to win matches?). Throughout the focus group, sub-questions from the pre-prepared script were used to collect further information if required. Additional open-ended probes were also used if more detail was required from a participant (e.g. "Why?", "What makes you say that?", "Could you expand on that last point please?") (Smith et al., 1995).

Data analysis

The recorded interviews were transcribed verbatim. The transcripts were then read several times by the lead author to enhance familiarity with the data, which was subsequently analysed inductively and thematically (Braun & Clarke, 2006). Following the thorough reading of the transcripts, initial codes were generated. This phase involved the production of initial codes from the transcripts which linked to a common theme or idea and refer to the most basic segment, or element, of the raw data (Boyatzis, 1998). Next, similar codes (i.e. quotations/themes) were identified throughout the transcripts, which were then sorted and extracted into groups to develop higher order themes. These higher order themes were categorised into singular topics which formed the results of the study. To ensure trustworthiness of the data and enhanced credibility of the data's interpretation (Smith, 2018), a relativist approach was adopted (Smith & McGannon, 2017). The lead author frequently discussed the analysis and findings of the transcripts with members of the research team, who acted as "devil's advocate", questioning the lead author on the method of analysis and the themes generated from the transcripts. In order to enable naturalistic generalisability of the data, contextual detail using direct quotations and interactions between the participants and the researcher were presented to allow the reader to make connections to their own experiences (Smith, 2018).

Results

The following results have been broken down into five sections: travel fatigue, inability to switch off from football, perception of team meetings, listening to music and internal pressure to succeed. Names and locations have been removed where appropriate in the interest of anonymity.

Travel fatigue

Fatigue from travel was cited by several members of the squad, with greater perceptions of fatigue dependent on travelling distance.

Participant 7 *– I think that's one of the main things, because over the season we'll do most likes of eight or nine away trips to London, pretty much, Brighton, so it is mentally demanding, but I think it's a lot worse if you're not used to it.*

Participant 8 – *Yeah I think it's like that with us, we're in full time, so we're in everyday, so we get like one day off a week, but then like on a weekend so we played XXXXXX at the weekend and erm, so we have been in all week, and then it comes to Saturday morning and we're traipsing all the way up to XXXXXX, and it's just like, you know, you don't get a break from it, so when it's an away trip it can be quite, mentally take over, just kinda feel like it's consumed you almost and yeah you're not getting time to switch off, so when you come home on a Friday, you know you'll sit down and have your dinner but then you're up again the next day and travelling and you're away for the whole weekend.*

Erm so sometimes you know just the luck of the draw if you have a long place to travel to it can be quite mentally exhausting, yeah.

Travel had an additional effect on perceived training readiness and performance

Participant 2 – *So we've had times where its took us that long to travel and by the time we get there, the next day we're training and stuff, so it is tough to recover from that……you know, yeah…*

Participant 5 – *I think we're obviously fortunate that probably XXXXXX is a lot smaller than what XXXXXX would be, and that the travel wouldn't be sort of the extreme relation to this article. Like, I'd say for the majority of us it would be about less than 30 miles each way, like, but, obviously yes for international matches abroad we'd seem to go out of like, XXXXXX which is two hours on top of before you even start to fly.*

Interviewer – *Yeah.*

Participant 5 – *And then just through no fault sometimes of the XXXXXX, they go the less direct way, so we go via somewhere else, erm, just probably to save a bit of cost, but yeah so, by the time you get there you probably are mentally sort of drained 'cause you have been on your feet or you have been travelling or you've maybe worked the day before and then had the travel with football teams. So, the last thing you want to do is go out and train the next day. But erm, we would normally go out and train obviously the next day after all the travelling for maybe 24 hours, it's just, it's tiring like.*

Participant 1 – *Erm, some- sometimes like there's are situations you're not getting there til 2 o clock in the morning, and then you're being asked, obviously we get up at normal time, even if the time zone has changed, you know, were trying to stick, getting in their time zone. We're getting up at 9* *o'clock and training by maybe 11 or 12 that day, so, ah, it's just what the girls are saying there, about you being mentally fatigued as well as physical.,*

Inability to switch off from football

Likely due to a more infrequent playing schedule in comparison to men's football, the impact of match-play in isolation received little attention in the focus groups. However, the general overall perceived heavy exposure to football related activity was frequently mentioned.

Participant 9 – *Yeah I just think about everything I do is football. When I go home, my dad's got football on and it's like all of a sudden "how was your game?" and it's like "fu-".*

Laughter

Participant 9 – *To talk about it again, then you go on social media, and all, all you'll see is FA (Football Association), the WSL (Women's Super League) you know, so it's all football. It's…you can't get away from it, don't get me wrong, I love social media, I go on it all the time, but it is everywhere. You go watch it on TV, you've now got Alex Scott and sportswomen working on there. You can't literally get away from it.*

Laughter

Participant 9 – *Which is good, brilliant for the women's game, but we are in this bubble at the minute, we can't get out of.*

Participant 6 – *Yeah.*

Laughter

Participant 8 – *We just need to stop her talking!*

Laughter

Interviewer – *No. Be as honest as you want!*

Participant 8 – *But I get what you mean, about like, say like I've just had a heavy week, and the game's on at the weekend like, it'll be on in the house, and I can't think of anything…*

Participant 9 – *Yeah.*

Participant 8 – *…like, I don't even wanna watch it like. That, because I'm like "this is still football like", and that's all I hear. Sometimes I just wanna switch off.*

Participant 9 – *and Match of the Day is on, and the woman from the WSL (Women's Super League) show hasn't even come on yet, oh top!*

The need for a break from football was raised.

Participant 2 – *We don't really get a break, especially in the campaign. So we have a few weeks off in Christmas time, but apart from that, we're just like constant.*

Participant 1 – *Because we finished last season, we finished end of August and then we're straight into these qualifiers, and then we obviously had erm, XXXXXX and, erm, oh, is that this year?*

Participant 2 – *XXXXXX?*

Participant 1 – *Oh yeah, XXXXXX last year and XXXXXX. This year's been kinda constant since, since then. Because the way this season works, it usually coincides with our season finished, and a new campaign is starting, and it'd be the - the same next year because the qualifiers start again in September.*

Participant 2 – *Yeah.*

Participant 3 – *Even though your body needs it physically as well, mentally you do need a break like.*

Participant 2 – *Yeah.*

Participant 3 – *You're with the same people all year like three or four times a week. Sometimes it's nice just to get two weeks off where you don't have to think about football. Just have some downtime where you can kinda do whatever you want with your evenings.*

Participant 1 – *Be normal for once. Be a normal person.*

Participant 2 – *Yeah. Because we're obviously cause we're not like professional setup, we train in the evenings and we train on weekends. So there's sometimes we'll be out on a Sunday all day because that's when our club trains. Sunday morning and then Sunday afternoon, and then Monday, like Tuesday was. Thursday, so we'll be out a lot training. And obviously you're working in the day and stuff. So there is points in the year where you're like, just need….*

Participant 5 – *Need a holiday.*

Participant 2 – *You do, you do like, you become tired, a wee bit tired.*

Fatigue experienced in team meetings

A key point commonly raised in the focus groups was the perceived unnecessary length of the team meetings used to prepare for upcoming international matches. These team meetings, they suggested, could last up for two hours.

Participant 6 – *But if it's constant, ergh, just flat and going over the same thing over and over and over, it just kills me, drains the life out of me.*

Participant 8 – *Yeah. I think in this environment as well, you come into camp and today like we've had like heavy day, we've been trained twice and like everyone's physically and mentally already drained, and then you have a meeting and it's like, oh my God, I mean the meetings have lasted a good two hours.*

Participant 6 – *Yeah.*

Participant 8 – *And when the meeting's done, you're going to bed. You're sitting in the meeting, trying not to fall asleep like, it gets that bad but it's the information like XXXXXX says, it's repetitive,* *and it's repetitive and it's going round in circles. Yeah and then obviously you're going to bed and then the next day you're waking up and you're shattered, like, it's just pointless really.*

Participant 6 – *Yeah.*

Participant 8 – *There's just no point. There's no need for it.*

Participant 7 – *I think in the last camp that happened, and we didn't have like one minute for the first like four days.*

Participant 6 – *Yeah.*

Participant 7 – *It was like a meeting in the morning, and at lunchtime there was a meeting about somebody else had come wanting something. And then in the afternoon there was another meeting, oh in the night time, there was another meeting. It came to a point where I was like, I don't mind a meeting, but I don't know what's going on here. I don't know why we're having this meeting like.*

To improve team meetings, a shorter duration length with more concise information was proposed.

Participant 8 – *There's just no need to have prolonged meetings like, like literally only need to be 20 – 30 minutes max, like.*

Participant 9 – *Yeah.*

Participant 8 *– There's just no need. Anything more than that, it's just repetition.*

Participant 9 – *The thing is, if you don't have that meeting there, you just say, look we'll have a quick five minutes before, ok, everyone could have had that nap in their room, then got psyched up a bit more in here, and we're on the bus listening to our music ready to go. Instead we're doing it in the reverse order when we have to be down here an hour and a half early, and then we're there and then we're knackered.*

Half time team talks were also critical in their delivery.

Participant 1 – *Just for me personally, sometimes I know it's not before kick-off, but at half time like, if a coach comes in and talks for the whole fifteen minute period at half time, I just find that really draining.*

Participant 2 – *Yeah.*

Participant 3 – *Yeah.*

Participant 1 – *Because at half time I just want say three or four points of either what we're doing, you know a mixture of make sure what we're doing well and what we need to improve on, but I want it, like short concise instead of fifteen minutes of talking because it's yourself as a player, you want a few minutes to switch off and relax again at half time before you obviously go back out again. I just find it draining sometimes if someone just talks constantly, you know for the fifteen minutes.*

Participant 5 – *Yeah, I agree.*

Interviewer – *What are your opinions on the half time then, team talk?*

Participant 3 – *Yeah even getting yourself ready, if the manager's talking, you feel like you can't get up and go to the bathroom and get a drink and get something you know, to eat, cause you feel like you need to sit there and give him your attention, and then when he's finished you're rushing yourself to get back out and get on the pitch again so, so I think as XXXXXX said, making it short, concise, two or four points you can kinda remember.*

Anecdotes of effective half time team talks at domestic clubs were shared.

Participant 2 – *What I like, like at our, at our club, erm, when we come in at half time, our coach kinda stays in the background, kinda gives us a minute, that…*

Participant 4 – *Yeah.*

Interviewer – *Yeah.*

Participant 4 – *Amongst ourselves.*

Participant 2 – *Kinda a discussion amongst ourselves and get erm, your drinks or your snacks or whatever, and he gives us our time to kinda, just have a good chat amongst yourselves, and that's when he comes in. But as XXXXXX says like, I think it's key that you do get told about this is what we need to fix, and this is how we need to fix it. So when we go out for the second half, we can obviously, you can, yeah, fix what's not working.*

Listening to music

Music played a large role in player preparation before a match. The role of music acted as both relaxation in the hours leading up to the match.

Participant 1 – *I think a lot of us on the way to games and stuff, lots of people prefer to listen to music by themselves, or there are a couple of people with headphones in, but all of our team would try and zone out, try and get themselves in the zone, try and listen to some music, you know if you're traveling by bus or whatever to the game. Erm because obviously, everyone has a preference of what they're gonna listen to before the game. Erm but that's on the way to the game, most people would kinda do that.*

Participant 2 – *I think it's very different in terms of club matches and international match days, it's completely different for everyone. Well maybe not you, you don't do anything!*

Laughter

Participant 2 – *Club matches you're going from work, and kinda picking people up whatever.*

Interviewer – *Yeah.*

Participant 2 – *But in terms of international games like, it's nice to, you know when you get time during the day, to just lie and chill and listen to your music, to just lie on top of your bed and just yeah, get some peace for a while.*

Music acted as more of a motivating factor closer to kick-off.

Participant 6 – *It's changing room, music on, getting ready to warm-up, and then going out warming up.*

Participant 9 – *Yeah 45 minutes before innit, when we go out isn't it?*

Participant 6 – *I think it's the same after you come in from the warm-up, music on again, kinda buzzing, everybody's kinda geeing each other up.*

Internal pressure to succeed

Players frequently cited a pressure from within their own team to succeed, which negatively impacted on perceived performance.

Participant 8 – *It comes from those around you like, like in the environment it could be coaches or it could even be players in some, erm situations. Like it could be part of the team, or the players really get on at each other, and if you do, you're doing something bad straightaway, they're on your case. And then that could lead you to feel under pressure every time you get the ball, and do it right this time, we need to do it right, or they're getting on you again, or it could be coming from the coaches. So I feel it could be coming from around as well, erm, yeah.*

Participant 10 – *I think like, I think worst thing is when you know you've done something wrong, and you hear it coming from the sideline, and you're like, I know, I just did it myself, like, I don't need someone screaming at me telling me I've done it.*

Interviewer – *Yeah.*

Participant 10 – *And then like XXXXXX said, the next time you get the ball, the last thing you wanna do is mess up.*

Participant 8 – *Uh huh.*

Participant 10 – *But then you just get into this mindset, and then like, just put pressure on yourself.*

Participant 9 – *Yeah.*

Participant 8 – *Yeah, yeah.*

Participant 10 – *And you're more likely to actually make a mistake.*

Participant 9 – *But then like as well, with XXXXXX I start thinking what does he want me to do? I've got the ball at my feet and I should be able to make my own decisions, I can see the pitch. But I'm thinking actually…*

Participant 6 – *It becomes robotic.*

Participant 9 – *…he wants me to hit that, I know he does. And you hesitate, and by the time you hesitate someone's straight on you and takes the ball off you.*

Participant 6 – *Yeah.*

Participant 9 – *But really you should just play the game with freedom, and that's why you're here, do you know what I mean?*

Interviewer *– Yeah.*

Participant 9 – *You should, you've got your strengths, use them, but unfortunately, I think that's a lot of pressure, and some team mates are like that, some team mates would be like, erm not here, but like that.*

The pressure to succeed appeared to negatively impact on younger and inexperienced players.

Participant 7 – *But I think we're alright because we're older, but the kids.*

Participant 8 – *Yeah the kids.*

Interviewer – *Really?*

Participant 7 – *Yeah go into holes, they're really good players but they just don't want to play.*

Participant 6 – *Like XXXXXX for example, she couldn't handle the pressure like. She was a good player that was in before, and she just couldn't handle the pressure, the constant pressure that was under, so it's just not….*

Interviewer – *Yeah.*

Participant 7 – *…and there's loads of girls in about a year, loads that have just had a fall out over it, who maybe aren't strong enough to, you know.*

Interviewer – *Yeah.*

Participant 7 – *Some of us are more, right I enjoy this experience, more than worrying about what you're gonna say.*

Participant 8 – *Yeah.*

Participant 7 – *And the things that they've been told over the years. It's like if we weren't mentally tough, there's girls who just haven't, never come back.*

Participant 8 – *Crumble…*

Participant 7 – *Actually just stuck through it for some reason.*

Participant 9 – *Yeah.*

Participant 7 – *But I don't know why!*

Laughter

Participant 8 – *We've just managed to come back again.*

Interviewer *– Yeah.*

Participant 8 – *And so many talented players have just walked away because they can't handle it. Can't put themselves through it again, can't cope with the pressure and, you know, it's not fair is it?*

Differences were apparent between international and domestic settings.

Interviewer – *How do you compare that to domestic football?*

Participant 2 – *You definitely feel more of a confident player in terms of club level, I would say.*

Participant 3 – *Yeah.*

Participant 2 – *You kinda get to express yourself more I suppose. And obviously, erm, probably be in that kind of environment a lot more, you know with other, like you spend a lot of time with club, club, erm, mates obviously so, I suppose you don't really have the pressure, like it doesn't compare.*

Participant 3 – *Yeah*

Participant 2 – *It just doesn't compare at international level. Like, at all.*

Interviewer *– Yeah.*

Participant 2 – *Erm, yeah obviously you wanna go in and win. I suppose we go in the club games wanting to win them. Especially this year like, we go in wanting to win because we know we're capable of winning them, so yeah.*

Participant 4 – *It's a lot different for me because I'm one of the younger ones here. So it's like, less pressure but there's more pressure because I have to prove I'm good enough to be. I go out in the club I'm still one of the younger ones but more experienced in their groups.*

Participant 2 – *Yeah.*

Participant 4 – *But with me being, so there's that different expectation or pressure. I feel that, yeah.*

Participant 2 – *Yeah.*

Interviewer – *What about yourself, anything to add?*

Participant 3 – *Yeah I don't really know, I don't really know how to describe the difference between international and club, it is just different emotion whenever you go out to play.*

Participant 2 – *Yeah.*

Participant 3 – *But if you do get in to play league, cups, finals like that, there still is that expectation that you have to step up and like, the international players have to be big players on those occasions, and you have to perform well, but I don't know, you probably don't get as overwhelmed, or in awe of the occasion as you would at international level.*

Discussion

Whilst the physical demands of elite female football have been well investigated (Datson et al., 2017; Bradley et al., 2010), little is known about the impact of mental fatigue. Despite six original studies investigating the effects of mental fatigue on football-specific performance (Smith et al., 2018), they were limited by the ecological validity of the tasks used to induce mental fatigue, and lack of female representation. The aim of the present study was to therefore identify the real-life causes of mental fatigue in elite female football players, using several relevant topics from anecdotal quotes in elite football and themes theorised/demonstrated in recent publications to inform the choice of questions (Thompson et al., 2018; Smith et al., 2018; Coutts, 2016; Moore et al., 2017). The focus groups revealed a perceived negative impact of travel, combining work/education commitments with football, and the nature of team meetings as mentally fatiguing and detrimental to football-specific performance. The information gathered from these focus groups have provided a novel insight into “real-world” psychological issues which may aid future mental fatigue research and practice.

The impact of air travel on lower sleep duration and impaired football training performance amongst several players in the squad was cited in the focus groups. Knowledge on the impact of travel on sleep duration is not available in female football research, gender differences in sleep problems have been reported in the literature, with females from a general population experiencing more trouble falling asleep, waking during the night and feeling un-refreshed upon waking than males (Groeger, Zijlstra, and Dijk, 2004). Previous literature in air travel and sleep quantity is limited to elite male football, but has demonstrated that international flights (10-18 hours) significantly reduces sleep quantity in the early phases of an international training camp (Fullagar et al., 2016; Fowler et al., 2015). In both studies, negligible effects were found for the effects of air travel on perceived recovery and preparedness to train and play, which was contrasting to the current findings from the focus groups. This may be explained by the validity of the psychometric tools used, or perhaps a more prominent psychological issue associated with a series of transient negative effects, collectively referred to as 'travel fatigue', which consists of anxiety concerning the journey and the significant change to daily routine associated with international matches (Waterhouse, Reilly, and Edwards 2004). Indeed, many of the players in the current study voiced such concerns as taking time away from work and the anxiety of travelling home to return to work, domestic duties and club football commitments. To improve sleep, players may benefit from education and support with sleep quality/quantity. In elite female netball, a 60-minute education program on sleep hygiene with practical advice (sleep routine, lighting, avoidance of caffeine and light emitting technology, and relaxation strategies) significantly resulted in increased sleep quantity during a pre-season training camp (O’Donnell and Driller, 2017). Sleep hygiene education has also improved sleep quality/quantity for females in full-time employment (Chen, Kuo, and Chueh, 2010). Further research is required in elite female football to understand the impact of travel on sleep quality/quantity, preparedness to train, and the impact of sleep hygiene education programs.

The education and work commitments of players led them to support proposals for a break from football-related activity. In order to commit to international call ups, players were required to take annual leave from their jobs or reduce the focus placed on education and work commitments. With players studying and/or working full-time and domestic football matches predominantly played on weekends and consisting of frequent travel demands, it is challenging for elite female players to find free time to unwind physically and mentally. Previous focus group research in elite female footballers (Gledhill and Harwood, 2015) cited the difficulty of combining education and football commitments and a lack of female football career opportunities. This study subsequently proposed that players, coaches, teachers and parents should adaptively interact to produce an optimal talent development learning environment for elite football players. Examples of this support included football-specific advice and guidance (e.g. psychological skill development), realistic expectations and role strain management. Future research and practice are required to further investigate and implement a support network to decrease the strain of dual career, therefore allowing more time to focus on football-specific activity and reducing feelings of mental fatigue.

An additional theme captured from the focus groups was negative connotations towards prolonged information intake from coaching staff, predominantly in team meetings and in the half time period of matches. The information received in meetings was often perceived to be irrelevant or repetitive, and led to feelings of decreased arousal and increased mental and physical fatigue. Only recently has sustained listening and its impact on arousal and mental fatigue levels been investigated in normal hearing populations. Using a 50-min auditory choice task, Moore et al., (2017) reported decreased task performance and increased subjective mental fatigue pre-post trial, whilst event-related potentials revealed changes in neural activity consistent with decreased arousal. This decrease also revealed a significant, positive correlation with subjective report of reduced motivation. Indeed, many of the meetings detailed in the focus groups were significantly longer than the 50-min task used by Moore et al., (2017). In addition, despite the topic of football likely to be more interesting than a generic auditory task to an elite playing population (and therefore in theory less likely to incur changes in arousal and fatigue), it is evident that the perceived irrelevant content and repetition of information is what likely caused the negative emotions towards the meetings. In a training week preparing for a match, the length of time spent together in elite female football is brief but full of many commitments (i.e. training, playing, media), making it challenging for a coach to deliver the information necessary to be prepared for the upcoming opposition. However, the findings from the focus groups suggests that coaches must adopt a concise approach free from repetition which engages the concentration of the players.

Of particular interest in the current study was to elucidate the activity profile of elite female football players in the lead up to a match. The focus groups revealed that music played a large role in the dressing room pre-match. Mixed effects of music are evident in female football literature, with warm-up music shown to have a positive impact on repeated sprint ability in female footballers (Tounsi et al., 2019), and conversely no influence on football-specific running and heart rate/rating of perceived exertion (Young et al., 2009). Indeed, as these are isolated performance tasks, the impact of warm-up music on match-play is unknown in female football. However, research in male academy football has shown that music in conjunction with imagery is associated with increased perceived match performance (Pain, Harwood, and Anderson, 2011). Music therefore appears to have the ability to inspire, motivate and heighten perception of task performance. The focus groups showed that routines are typically regimented (i.e. set routine of a warm-up, listening to music, receiving a team talk and entering a team huddle) and do not elicit mental fatigue. These findings demonstrate that players in the current study do not enter match-play mentally fatigued, which is interesting considering that mental fatigue has been consistently induced immediately prior to the football-specific performance task (Smith et al., 2018). Future research is required to investigate the presence of mental fatigue at different time points (e.g. during/after match-play, pre and post-training, post-media commitments) to understand its potential onset period in real-life settings.

A further finding from the focus groups was the perceived greater internal pressure to win matches at international level in comparison to the players' respective domestic leagues. This was possibly due to low world ranking place of the nation and results in previous international tournament qualification campaigns of those interviewed, which likely lessens external (supporters, media) expectations. This internal pressure appeared to come from the style of coaching during already high pressurised match-play scenarios. Indeed, it is commonplace for athletes to receive tactical information, instructions and feedback to enhance performance (Porter, Wu and Partridge 2010), which can come in explicit (consciously clear and obvious) or implicit (the need for an athlete to take more ownership of a scenario) forms. Research has shown that explicit forms of feedback are inversely related with playing experience and can be detrimental to sporting performance (Buszard, Farrow, and Kemp 2013). The reported overuse of explicit feedback during match-play from the focus groups appears to stifle concentration levels and freedom of thought. Elite players are likely to benefit from implicit instructions which allow them to solve movement patterns and environmental cues in a match, something which has been previously shown to improve perceptual cognitive skills (Farrow and Abernethy 2002).

Conclusion

The present study aimed to provide novel findings related to the real-life experiences of mental fatigue from elite female football players. Many players felt a discomfort in being taken away from their daily routine and felt over absorbed by the constant exposure to football related activity. In addition, team meetings were often perceived as being unnecessarily long and met with frustration and low arousal. These findings provide useful applications for both future research and practice. Subsequent research on prolonged listening (using a simulated team talk or an auditory task) could aid in the development of a more ecologically valid task to induce mental fatigue, as opposed to the commonly used modified Stroop task (Thompson et al., 2018). Practitioners and coaches may also wish to consider alterations to daily practice in training camps, such as the timing, content and duration of team meetings, providing players with free time if possible, and the modality of coaching instructions during matches.

Conflicts of interest

There are no conflicts of interest for this study. Furthermore, no external financial support was required.

References

Badin, O. O., Smith, M. R., Conte, D., & Coutts, A. J. (2016). Mental fatigue: impairment of technical performance in small-sided soccer games. *International Journal of Sports Physiology and Performance*, *11*(8), 1100-1105.

Bauman, N. J. (2016). The stigma of mental health in athletes: are mental toughness and mental health seen as contradictory in elite sport?. *British Journal of Sports Medicine*, *50*(3), 135.

Bensing, J. M., Hulsman, R. L., & Schreurs, K. M. (1999). Gender differences in fatigue: biopsychosocial factors relating to fatigue in men and women. *Medical Care*, *37*(10), 1078-1083.

Boksem, M. A., Meijman, T. F., & Lorist, M. M. (2005). Effects of mental fatigue on attention: an ERP study. *Cognitive Brain Research*, *25*(1), 107-116.

Boyatzis, Richard E. *Transforming qualitative information: Thematic analysis and code development*. Sage, 1998.

Bradley, P. S., Di Mascio, M., Peart, D., Olsen, P., & Sheldon, B. (2010). High-intensity activity profiles of elite soccer players at different performance levels. *The Journal of Strength & Conditioning Research*, *24*(9), 2343-2351.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77-101.

Buszard, T., Farrow, D., & Kemp, J. (2013). Examining the influence of acute instructional approaches on the decision-making performance of experienced team field sport players. *Journal of Sports Sciences*, *31*(3), 238-247.

Carling, C., Lacome, M., McCall, A., Dupont, G., Le Gall, F., Simpson, B., & Buchheit, M. (2018). Monitoring of post-match fatigue in professional soccer: welcome to the real-world. *Sports Medicine*, *48*(12), 2695-2702.

Chen, P. H., Kuo, H. Y., & Chueh, K. H. (2010). Sleep hygiene education: efficacy on sleep quality in working women. *Journal of Nursing Research*, *18*(4), 283-289.

Coutinho, D., Gonçalves, B., Travassos, B., Wong, D. P., Coutts, A. J., & Sampaio, J. E. (2017). Mental fatigue and spatial references impair soccer players' physical and tactical performances. *Frontiers in Psychology*, *8*, 1645.

Coutinho, D., Gonçalves, B., Wong, D. P., Travassos, B., Coutts, A. J., & Sampaio, J. (2018). Exploring the effects of mental and muscular fatigue in soccer players' performance. *Human Movement Science*, *58*, 287-296.

Coutts, A. J. (2016). Fatigue in football: it's not a brainless task!. *Journal of Sports Sciences*, *34*(14), 1296.

Datson, N., Drust, B., Weston, M., Jarman, I. H., Lisboa, P. J., & Gregson, W. (2017). Match physical performance of elite female soccer players during international competition. *The Journal of Strength & Conditioning Research*, *31*(9), 2379-2387.

Farrow, D., & Abernethy, B. (2002). Can anticipatory skills be learned through implicit video based perceptual training? *Journal of Sports Sciences*, *20*(6), 471-485.

Fowler, P., Duffield, R., Howle, K., Waterson, A., & Vaile, J. (2015). Effects of northbound long-haul international air travel on sleep quantity and subjective jet lag and wellness in professional Australian soccer players. *International Journal of Sports Physiology and Performance*, *10*(5), 648-654.

Fullagar, H. H., Duffield, R., Skorski, S., White, D., Bloomfield, J., Kölling, S., & Meyer, T. (2016). Sleep, travel, and recovery responses of national footballers during and after long-haul international air travel. *International Journal of Sports Physiology and Performance*, *11*(1), 86-95.

Gledhill, A., & Harwood, C. (2015). A holistic perspective on career development in UK female soccer players: A negative case analysis. *Psychology of Sport and Exercise*, *21*, 65-77.

Gledhill, A., Harwood, C., & Forsdyke, D. (2017). Psychosocial factors associated with talent development in football: A systematic review. *Psychology of Sport and Exercise*, *31*, 93-112.

Groeger, J. A., Zijlstra, F. R. H., & Dijk, D. J. (2004). Sleep quantity, sleep difficulties and their perceived consequences in a representative sample of some 2000 British adults. *Journal of Sleep Research*, *13*(4), 359-371.

Harper, L. D., & McCunn, R. (2017). “Hand in Glove”: using qualitative methods to connect research and practice. *International Journal of Sports Physiology and Performance*, *12*(7), 990-993.

Lorist, M. M., Boksem, M. A., & Ridderinkhof, K. R. (2005). Impaired cognitive control and reduced cingulate activity during mental fatigue. *Cognitive Brain Research*, *24*(2), 199-205.

Moore, T. M., Key, A. P., Thelen, A., & Hornsby, B. W. (2017). Neural mechanisms of mental fatigue elicited by sustained auditory processing. *Neuropsychologia*, *106*, 371-382.

O'Donnell, S., & Driller, M. W. (2017). Sleep-hygiene Education improves Sleep Indices in Elite Female Athletes. *International Journal of Exercise Science*, *10*(4), 522.

Pain, M. A., Harwood, C., & Anderson, R. (2011). Pre-competition imagery and music: The impact on flow and performance in competitive soccer. *The Sport Psychologist*, *25*(2), 212-232.

Porter, J., Wu, W., & Partridge, J. (2010). Focus of attention and verbal instructions: Strategies of elite track and field coaches and athletes. *Sport Science Review*, *19*(3-4), 77-89.

Smith, B. (2018). Generalizability in qualitative research: Misunderstandings, opportunities and recommendations for the sport and exercise sciences. *Qualitative Research in Sport, Exercise and Health*, *10*(1), 137-149.

Smith, J. A. (1995). Semi-structured interviewing and qualitative analysis. *Rethinking Methods in Psychology*. Sage.

Smith, M. R., Coutts, A. J., Merlini, M., Deprez, D., Lenoir, M., & Marcora, S. M. (2016). Mental fatigue impairs soccer-specific physical and technical performance. *Medicine & Science in Sports & Exercise*, *48*(2), 267-276.

Smith, M. R., Fransen, J., Deprez, D., Lenoir, M., & Coutts, A. J. (2017). Impact of mental fatigue on speed and accuracy components of soccer-specific skills. *Science and Medicine in Football*, *1*(1), 48-52.

Smith, B., & McGannon, K. R. (2017). Developing rigor in qualitative research: Problems and opportunities within sport and exercise psychology. *International Review of Sport and Exercise Psychology*, *11*(1), 101-121.

Smith, M. R., Thompson, C., Marcora, S. M., Skorski, S., Meyer, T., & Coutts, A. J. (2018). Mental fatigue and soccer: Current knowledge and future directions. *Sports Medicine*, *48*(7), 1525-1532.

Smith, M. R., Zeuwts, L., Lenoir, M., Hens, N., De Jong, L. M., & Coutts, A. J. (2016). Mental fatigue impairs soccer-specific decision-making skill. *Journal of Sports Sciences*, *34*(14), 1297-1304.

Thompson, C. J., Fransen, J., Skorski, S., Smith, M. R., Meyer, T., Barrett, S., & Coutts, A. J. (2018). Mental fatigue in football: Is it time to shift the goalposts? An evaluation of the current methodology. *Sports Medicine*, *49*(2), 177-183.

Tounsi, M., Jaafar, H., Aloui, A., Tabka, Z., & Trabelsi, Y. (2019). Effect of listening to music on repeated-sprint performance and affective load in young male and female soccer players. *Sport Sciences for Health*, 1-6.

Waterhouse, J., Reilly, T., & Edwards, B. (2004). The stress of travel. *Journal of Sports Sciences*, *22*(10), 946-966.

Williams, A. M. (2000). Perceptual skill in soccer: Implications for talent identification and development. *Journal of Sports Sciences*, *18*(9), 737-750.

Young, S. C., Sands, C. D., & Jung, A. P. (2009). Effect of music in female college Soccer players during a maximal treadmill test. *International Journal of Fitness*, *5*(2), 31-36.

9 – DISCUSSION

9.1 – Summary of thesis findings

Mental fatigue in football is a novel research area limited to six original investigations. These previous studies possess several limitations including the low ecological validity of the tasks used to induce mental fatigue and lack of elite player representation. The present thesis aimed to challenge and examine the methodology of the mental fatigue in football research, investigate the relevance of the modified Stroop task (the most commonly used task to induce mental fatigue) in mental fatigue research, and subsequently investigate the real-life causations of mental fatigue in elite football. Chapter 4 provided a narrative review of the methodology, highlighting the significant challenge of measuring mental fatigue in elite football settings, and the low ecological validity of the tasks used to induce mental fatigue. Chapter 5 subsequently highlighted limitations of using the modified Stroop task in mental fatigue in football research by revealing its subsequent impact on subjective boredom (which could not be distinguished from subjective mental fatigue). In chapters 6 and 7, surveys revealed a limited impact of football and lifestyle related tasks on mental fatigue and performance in professional male and academy players respectively. This included travel to matches/training, intake of tactical information, media demands and educational commitments, of which some have previously been theorised to be associated with experiencing mental fatigue in football (Coutts, 2016). Conversely, focus groups with elite female football players highlighted the negative psychological impact of international travel, prolonged and excessive team meetings, managing football commitments with work and education, plus internal “pressure to win”.

The following discussion will integrate the findings to address the following themes; i) how relevant are the cognitive tasks currently used to induce mental fatigue in football research? ii) what are the real-life pre-match cognitive activities performed by elite football players? iii) at which other time points may mental fatigue impair football performance? The discussion also addresses the limitations of the thesis and provides suggestions for future research and practical applications.

9.2 - How relevant are the cognitive tasks currently used to induce mental fatigue in football research?

Demands of the cognitive tasks

The first aim of the thesis was to challenge the use of the current cognitive tasks to induce mental fatigue in mental fatigue in football research. Research has used predominantly the 30-min modified Stroop task (Coutinho et al., 2018; Smith et al., 2017; Badin, Smith, Conte, & Coutts 2016; Smith et al., 2016a; Smith et al., 2016b) and 20-min sport-specific motor task (Coutinho et al., 2017). As discussed in chapter 4, the tasks used in these studies likely do not match the high degree of variability in cognitive challenges related to football match-play. Elite football players frequently compete in various conditions, relating to playing surface, crowd interaction and ambient light available during the game. In addition, players are required to perform relevant defensive (e.g. committing to a tackle) or attacking (e.g. pass, shoot, dribble) actions under low or high amounts of pressure, whilst continually using information on the position, running direction and velocities of their teammates (and those of the opposition players) in relation to their own position. These decisions in match-play situations differ to the decision-making demands of a modified Stroop task. Decision making in elite sport can be difficult to quantify and explain. In elite sport, decision-making processes from a motor response are often made unconsciously without a thought process (Raab & Laborde, 2011; Kida, Oda & Matsumura, 2005). Decision-making in elite sport is often intuitive and enters consciousness only for a brief moment, and the information processed and ultimately acted on quickly accurately can be dependent on information specific to the situation (Sheppard & Young, 2006). If an action is highly trained and the decision to act upon it is made unconsciously, then it may be less likely to elicit a cognitive demand. Conversely, some actions in football are consciously made and require sustained attention and response inhibition (e.g. marking an opposing player, adhering to the tactical shape of the team), similar to the demands of the modified Stroop task. Chapter 5 of the current thesis demonstrated that the modified Stroop only reflects conscious congruent and incongruent task performance, and not unconscious performance (likely because the modified Stroop task is a novel task for participants which requires greater attentional demands). In summary it is concluded that the modified Stroop task only partially reflects the cognitive demands experienced in match-play, and further research must investigate real-life cognitive tasks performed by elite football players.

Presence of boredom when completing the cognitive tasks

A further pertinent issue with mental fatigue research is that it is difficult to distinguish between boredom using the available tools (Pattyn et al., 2008). Chapter 5 showed that when exposed to a 30-min modified Stroop task, participants reported increased boredom, demonstrating that the two constructs (mental fatigue and boredom) are not perceived as being entirely different. It is possible that intrinsic motivation was low when engaging in the modified Stroop task, which manifested in boredom. Cognitive activities such as the modified Stroop task likely provides a cognitive "underload" (Pattyn et al., 2008). Pattyn et al., (2008) theorised that compared to "overload" tasks (i.e. high cognitive engagement), an "underload" task provides a reduced cognitive challenge and is associated with mind wandering (i.e. boredom). These findings suggest that whilst the modified Stroop task may bear a resemblance to some real-world tasks that require prolonged vigilance and low cognitive engagement (i.e. repetitive factory or office-based tasks), more dynamic tasks like football require ecologically valid protocols to induce mental fatigue in future studies. Moreover, the emotional state of elite players in the 30-min period before a match is likely to vastly differ to the findings of the present research (mental fatigue, boredom). For example, it is more likely that elite players will experience feelings such as nerves, stress, anxiety, high arousal and high motivation. However, it remained unknown which activities players are exposed to in the acute stages before a match, which warranted further investigation. This will now be discussed in the following section.

9.3 - What are the real-life pre-match cognitive activities performed by elite football players?

Chapters 6, 7 and 8 investigated the activities performed by elite football players in the acute periods (up to two hours pre-match) leading up to a match. The purpose of these studies was to find a more relevant task to induce mental fatigue compared to the modified Stroop task. The results showed that players reported pre-match activities (i.e. listening to music, screen time activities) which had a generally low impact on mental fatigue. These main findings and their relation to previous research will be discussed in the following section.

Screen time

Survey studies (chapters 6 and 7) revealed that professional male and elite academy (U14 – U23) players cited screen time activities as a common past time in a two hour period before kick-off. These activities included watching videos (e.g. YouTube/Netflix), playing video games and using smartphone apps. In the current literature, little research has investigated the cognitive demands of these activities. Watching television (which may be a common pastime on a coach to a match or in a hotel prior to travelling) has been associated with "visual fatigue", when measured using surveys and objective eye blink rate frequency (Lambooij, Fortuin, Heynderickx, & Ijsselsteijn, 2009). The use of video games and smartphone apps have had a mixed effect on mental fatigue. In one study, the use of a 30-min smartphone puzzle app ("Brain it on") resulted in increased subjective mental fatigue and impaired performance in the Loughborough Soccer Passing Test (LSPT) (Greco et al., 2017). Whilst a progression in ecological validity, it is still questionable if football players would complete a cognitively demanding puzzle for an uninterrupted period of 30-min before a match, or if the LSPT is representative of the skill and decision-making demands of football match-play. Further work with higher ecological validity concluded that 30-min & 45-min of continuous exposure to social networking apps (e.g. WhatsApp, Facebook & Instagram) impaired passing decision-making in a 90-min simulated match. The study also revealed that 15-min exposure to the same condition did not impair passing decision-making (Fortes et al., 2019). Whilst pre-match activity duration was not measured in chapters 6 & 7 of the thesis, it is unlikely that professional male and academy players would be able to continuously use their smartphones 30/45-min in the two hours leading up to kick-off. Conversely, the use of video games has been associated with increased mood and reduced stress in university students (Russoniello, O'Brien, & Parks, 2009). Indeed, Aliyari et al., (2015) found that university students playing the popular video game FIFA 15 reported no impact on mental fatigue. These results must be interpreted with caution, as the duration of the games were not reported, nor was there a control group.

To summarise, watching videos, playing video games and using smartphone apps that are of intrinsic interest to an individual are unlikely to cause mental fatigue. In addition, during the two hour period before a match begins, it is also likely that due to other commitments (i.e. warm up, communicating with staff/team mates, team talk) such activities are brief in duration and interrupted, significantly reducing the time on task compared to aforementioned research (Fortes et al., 2019; Greco et al., 2017; Lambooij et al., 2009).

Music

The thesis demonstrated that music played an integral part of pre-match activity for professional male, elite academy and elite female players (chapters 6, 7 and 8). In professional male (chapter 6) and elite academy players (chapter 7), listening to music was the most common pre-match activity, whilst elite female players (chapter 8), cited music as being effective for both relaxation (several hours leading up to a game) and motivation (in the hour leading up to a match). This was in agreement with previous survey research (Laukka & Quick, 2013) which reported that music was used by elite Swedish athletes during pre-event preparations, warm-up, and training sessions; with the most common motives for listening to music being to increase pre-event activation, motivation, performance levels and to experience flow. Indeed, music has been shown to have a relaxing influence (Pelletier, 2004; Stratton & Zalanowski, 1984), increase levels of arousal (Bishop et al., 2014), decrease RPE during a sport-specific warm up period (Arazi, Asadi & Purabed, 2015) and improve perceived football match-play performance (Pain et al., 2011). Previous research has also shown that mental fatigue can be negated by high motivation/willingness to complete to a task (Boksem & Tops, 2008). Accordingly, it is likely that music has a positive influence on player preparation, through psychophysiological effects including increased motivation, readiness to play and arousal.

Caffeine

Caffeine is a stimulant which has been shown to enhance task switching ability (Einöther et al., 2010), reduce reaction times (Jacobson & Edgley, 1987), increase arousal (Barry et al., 2005) and increase football specific (LSPT) skill performance (Foskett, Ali & Gant, 2009). The consumption of caffeine pre-match was prevalent amongst professional male and elite female football players in chapters 6 and 8 (caffeine use was not queried in academy players in chapter 7). Consumption was in the form of beverages (e.g. tea, coffee, taurine drinks), tablets, gels, shots and chewing gum, which was typically ingested around an hour before a match by professional male players in chapter 6 (but unspecified by elite female players in chapter 8). This appears to be an optimal time period considering that caffeine has been shown to reach a peak plasma volume level between 30-75-min post-ingestion (Quinlan, Lane & Aspinall, 1997). Mechanistically caffeine increases the signalling availability of dopamine in the brain (Nall, Shakhmantsir, Cichewicz et al., 2016; Volkow, Wang, Logan et al., 2015), and previous work has theorised that decreases in dopamine (and increases in adenosine) occur during states of mental fatigue (Martin et al., 2018, Pageaux et al 2014). This may explain why caffeine has proven effective in reducing mental fatigue and subsequent cognitive task performance (van Cutsem et al., 2018; Azevedo et al., 2016).

Team talk

Receiving tactical information has been suggested as a risk factor for the development of mental fatigue (Coutts. 2016). This relates to prolonged listening (40 – 50-min) protocols which have been linked to reduced arousal and motivation (McGarrigle et al., 2017; Moore et al., 2017). In elite male domestic (chapter 6) and academy players (chapter 7), team talks were delivered approximately 20 and 30-min before kick-off and lasted approximately 7 and 10-min respectively. It is highly likely that these durations were not long enough to elicit mental fatigue (particularly when considering the duration of previous prolonged listening protocols). The content of these team talks is likely to consist of information already discussed in the lead up to matches (i.e. team meetings, general conversations between staff and players), and therefore include little novel information which ultimately is unlikely to provide a cognitive demand. Furthermore, it would be anticipated that a team talk would contain uplifting and positive sentiments which motivate players, thereby increasing arousal and readiness to play.

Overall impact of common pre-match activities on mental fatigue and performance in elite football

In elite male domestic and academy settings, a pre-match team talk was reported to have a minimal effect on subjective mental fatigue (chapters 6 and 7). In addition, feelings of subjective mental fatigue 5-min pre-match were seldom reported. These findings suggest that despite mental fatigue being induced pre-task using 20 to 30-min protocols in the current research (Coutinho et al., 2018; Coutinho et al., 2017; Smith et al., 2017; Badin, Smith, Conte, & Coutts 2016; Smith et al., 2016a; Smith et al., 2016b), this is not a time point where mental fatigue is likely to occur in elite football.

Due to the mixture of pre-match activity (i.e. warm-up, receiving tactical information, changing into match kit), the cognitive activities cited by professional male and elite academy players in chapter 6 & 7 (watching videos, using smartphone apps, playing video games) are unlikely continuously engaged in for 30-min. Moreover, the use of music and caffeine likely increases arousal, motivation and readiness to play, thereby further reducing the likelihood of mental fatigue. The present evidence suggests that pre-match activities do not act as suitable time-point to implement ecologically valid protocols to induce mental fatigue.

9.4 - At which other time points may mental fatigue impair football performance?

The findings of chapters 6, 7 and 8 reported a minimal impact of pre-match activity on perceptions of mental fatigue and impaired performance in elite football, which contradicts suggestions in all previous literature investigating sub-elite and recreational players (Coutinho et al., 2018; Coutinho et al., 2017; Smith et al., 2017; Badin, Smith, Conte, & Coutts 2016; Smith et al., 2016a; Smith et al., 2016b). Therefore, it is imperative to understand different time points in which mental fatigue may negatively impact on football performance. The results of chapters 6, 7 and 8 provide discussion points for alternative causations of mental fatigue, with contrasting findings between gender and competitive level.

Match-play

Football match-play consists of prolonged vigilance, decision-making, constantly receiving and processing information in a dynamic environment, which is theorised to be mentally fatiguing (Coutts, 2016). Indeed, due to the dynamic nature of a football match, players rapidly process information from the location of the ball, teammates and the opposition. A match will also consist of frequent decision-making activities which are influenced by team tactics, technical ability and physical capacity (Williams, 2000). In this thesis, professional male players (chapter 6), elite academy players (chapter 7) and elite female players (chapter 8) all cited cognitive demands related to match-play. Chapters 6 and 7 reported that the most prevalent time period of perceived mental fatigue was immediately post-match. This was also found in research which reported post-match cognitive differentrial RPE (dRPE) 30-min post-match across a Premier League season (Barrett et al., 2018). Although only subjectively reported post-match, it is also possible that mental fatigue is experienced in the latter stages (i.e. final 15-min) of match-play. The latter stages of a match (final 15-min) have previously shown a decrease in running distances (Bangsbo, Krustrup & Mohr, 2005), goals scored (Abt et al., 2002), technical involvements (Rampinini et al., 2009), and technical performance (Rampinini et al., 2008). Whilst decrements in match-related performance have been associated with physical fatigue (Rampinini, Impellizzeri et al., 2008), it is possible that mental fatigue is a contributing factor, considering the impact of mental fatigue on impairment in attention (Chaudhuri & Behan, 2004), reaction times (Boksem et al., 2005), and slower adjustments in performance after errors (Lorist et al., 2005) during non-sport-specific cognitive tasks.

Based on these findings, caffeine may be a suitable ergogenic aid during the first half or at half time to reduce the risk of mental fatigue in latter stages of match. These time periods of a match may be optimal when considering the duration required (30 to 75-min) for caffeine to reach peak plasma levels (Quinlan et al., 1997). Caution is advised when prescribing caffeine, as considerations are advised for dosage, use of other nutritional aids (carbohydrates), tolerance, hydration status and plateau in performance gains from chronic use (Judelson et al., 2005; Quinlan et al., 1997). Despite individual differences, mental fatigue also showed continued elevation in some professional male and elite academy players 24 hours post-match (chapters 6 and 7). This may be related to quality of sleep, which is significantly impaired on match days (Fullagar et al., 2016a). In addition, clubs may plan recovery/training sessions the day after a match, and driving to training whilst already tired may also exacerbate the risk of mental fatigue. These suggestions are merely speculative and require future research.

Team meetings

Findings from professional male (chapter 6) and elite female (chapter 7) players showed that team meetings are a frequent activity experienced in elite football settings (team meetings were not investigated in elite academy players in chapter 7). Team meetings are often used to analyse previous matches, identify individual or team-based performance and tactically prepare for upcoming opposition. These meetings will consist of (but not limited to) watching video footage and listening to coaching instructions. The duration of these meetings varied in the studies, ranging from average duration of 26-min in elite male domestic football (chapter 6) and up to two hours in elite female settings (chapter 8).

The perception of these meetings vastly contrasted between studies. In professional male football (chapter 6), a team talk was met with a low perceived subjective feeling of mental fatigue, whilst the negative impact of team meetings on motivation and arousal were reported by elite female players whilst away on international duty (chapter 8). These differences can be explained by several factors. Firstly, the duration of the meetings (up to two hours) was significantly longer than previous aforementioned prolonged listening protocols which negatively impacted on motivation and arousal (McGarrigle et al., 2017; Moore et al., 2017). Secondly, domestic clubs likely have more frequent meetings which are shorter in duration, due to the greater amount of time spent together compared to international settings. For international players, the infrequent nature of international call-ups and lack of time together may result in longer meetings to address a greater amount of information required to be given in team meetings. This increased duration raises the requirement to listen for prolonged periods and intake additional information, therefore heightening the risk of mental fatigue. However, as the focus groups with elite female players (chapter 8) consisted of one international team (therefore all reporting to the same coaching staff), it remains difficult to generalise these findings. The variation in teams that participated in the professional male football survey (chapter 6) may have masked the negative perception of one individual club which may have also reported mentally fatiguing team meetings. The survey design also means it is difficult to probe deeper into meeting content and additional perceptions which may share similarities to mental fatigue (e.g. boring, tiring, draining), Conversely, qualitative research is flawed by the difficulty in recruiting sample sizes necessary to differentiate between various teams/playing standards. Future studies may benefit by combining both methods by incorporating a follow-up focus group interview based on the initial findings gathered from a survey.

Travel

Chapters 6 (professional male players) and 7 (elite academy players) of the thesis investigated the impact of travel to training sessions and away matches, whilst chapter 8 (elite female players) explored the demands of international travel. Overall, the impact of travel demands is dependent on travel distance/duration, which increases perceived mental fatigue. In the professional male and elite academy player surveys (chapters 6 and 7), travel to training and domestic away matches were met with low cognitive demand, whilst international travel demands impacted on sleep duration and quality, and subsequently perceived readiness to train for elite female players (chapter 8). Professional male (chapter 6) and academy players (chapter 7) were either a passenger in a car or drove themselves to training sessions, with an average journey duration of 39 and 33-min, respectively. The reported durations are significantly below previous research which have demonstrated subjective and objective mental fatigue after 90 to 120-min driving protocols (Zhao et al., 2012; Ting et al., 2009; Lal et al., 2002). Travelling as a passenger in a car/coach or using public transport and its impact on fatigue is yet to be investigated, and is limited to air travel (Fowler, McCall, Jones & Duffield 2017; Fullagar et al., 2016b). This research is warranted in football, as it is likely elite players in England will travel significant distances (e.g. London to Newcastle = ~ 400 km) via a car/coach to reach away matches, with accumulative distances likely greater in larger European countries (e.g. Spain, Germany, France). However, travel duration to away matches was not investigated in the current thesis. This was tested in pilot surveys but with the variation in travel throughout a season and difficulty for players to accurately recall this information, it was subsequently removed. Future research may benefit from quantifying domestic travel in a season and its impact on mental fatigue. Indeed, collecting subjective data on a match-day proves challenging (i.e. disturbing a player's match-day routine), although the use of retrospective RPE can be advocated, meaning subjective may still be accurately collected in the days following the match (Fanchini et al., 2017).

Media commitments

Exposure to media commitments is suggested to be a mentally fatiguing activity for elite football players (Coutts, 2016). This is plausible considering the potentially regular demands of speaking to various media outlets and being exposed to prolonged periods of listening and repetitive questions/conversations. However, for professional male players (chapter 6), media demands were reported to have a minimal effect on perceived mental fatigue. Players rarely completed media duties on a weekly basis in the English Football League and National League, with an average media commitment duration of approximately 15-min. With such infrequent and brief commitments, it appears the impact of media demands on mental fatigue were previously overestimated (Coutts, 2016). However, as chapter 6 failed to include truly elite (Premier League) domestic male players, it remains unknown how media commitments would compare at this higher level. The Premier League (along with other top European Leagues such as Serie A, La Liga and the Bundesliga) has greater television exposure, global interest and revenue compared to lower league standards (Millward, 2017). Future research may benefit from understanding the impact of media commitments and "press invasion" on players in the top European leagues.

Fixture congestion

The impact of congested fixture schedules on elite football players consists of various research which has examined the physical (Carling et al., 2016; Dupont et al., 2010) and technical (Folgado et al., 2015) aspects of football match-play, with findings suggesting there is an increased injury incidence during these schedules (Bengtsson et al., 2013; Carling et al., 2016; Dellal et al., 2015; Dupont et al., 2010). Aside from the physical consequences of fixture congestion, the perceived cognitive demands were yet to be investigated. In professional male (chapter 6), elite academy (chapter 7) and elite female players (chapter 8), the effects of congested playing schedules on mental fatigue produced varied findings. In professional male and elite academy players (chapters 6 and 7), fixture congestion (both travel and match demands) was perceived to have a minimal impact on mental fatigue. These findings in professional male settings (chapter 6) may be explained by prolonged exposure to this scheduling. For example, a significant proportion of the sample had played elite football for at least five years (in leagues which comprise of 46 league matches and domestic cup commitments), and it is plausible that this cohort were psychologically adapted to this schedule of matches. In elite academy players (chapter 7), matches were typically contested once a week. It is therefore likely that the lack of exposure to congested fixture periods did not provide players with enough exposure to provide an experienced and educated response. These claims however require further investigation.

By using focus groups with elite female players (chapter 8), a perceived "over-exposure" to football related activity was prevalent amongst the group, as opposed to a perceived demand of strictly fixture congestion (likely due to the reduced fixture scheduling compared to elite male football). This suggested that the domestic/international training and match demands, coupled with little time to relax, resulted in players citing the need for a break from football. These feelings may have been exacerbated in female football due to the full-time education/work commitments that did not allow players to be "fully professional". Indeed, work duties such as office roles alone have a cognitive (impaired cognitive task performance) and physical (heart rate variability, blood pressure) impact (Taelman et al., 2011; Hjortskov et al., 2004; Garde et al., 2002) which may affect subsequent football performance. In professional male football, players may have more free time considering they are unlikely required to have an additional job. Moreover, recovery days off are likely prescribed for the male players, whereas the female players may have to return to work/education in an already fatigued state. In elite academy football, despite full time education being prevalent, a day release (or half a day) from education may be common for players as well as frequent holiday periods (e.g. summer, festive breaks, half term). These frequent breaks allow for a greater physical and mental recovery window compared to female players who likely work throughout a calendar year. It is suggested that regular breaks are provided for football players, particularly for elite female players who must accommodate full time work and/or education commitments.

9.5 – Thesis limitations

Despite the novel findings reported in this thesis, limitations must be acknowledged. Firstly, despite the novel research which has provided evidence of ecologically valid alternative cognitive tasks performed by elite football players, the surveys used in chapter 6 and 7 were not psychometrically validated, and future research should aim to assess the construct validity of these tools. Next, further detail was required areas of the survey studies in chapters 6 and 7. For example, the areas of mental fatigue experienced during a match and in periods of fixture congestion were limited and may have yielded different results with subsequent questions. Furthermore, survey studies may only provide a current snapshot of behaviour and opinions, meaning that results may differ over time. Indeed, a football season can vary in terms of team/individual form, change of management, travel demands and fixture congestion, each of which may influence mental fatigue. It is possible that the results of the surveys in chapters 6 and 7 could have differed had they been administered at different time points in the season. Lastly, despite a large sample size of elite football players, they may not be a representation of all elite players in their respective leagues, which again could impact the study's findings.

9.6 - Future research and practical applications

When considering the low amount of peer reviewed evidence in mental fatigue in football literature, there is a requirement for additional research. The longitudinal daily monitoring of mental fatigue might detect for changes in seasonal variation, which could not be measured in this thesis. As mentioned previously, a single use of a survey may only provide a snapshot of one's lifestyle habits and perceptions, which likely fluctuate throughout a season. Wellness questionnaires are already used (but not validated) in elite football (Fessi et al., 2016; Noon et al., 2015; Buchheit et al., 2013), however no validated psychometric tool has been implemented to measure mental fatigue. Therefore, the inclusion of a mental fatigue in a daily monitoring tool would aid the understanding of perceptual mental fatigue throughout various periods of a season which may provide different demands (i.e. congested fixture schedule, number of training session, increased travel demands). Secondly, as the current thesis has clearly shown little perceived impact of mental fatigue on performance in elite football settings, and therefore contrasting findings to previous research in non-elite cohorts (Coutinho et al., 2018; Coutinho et al., 2017; Smith et al., 2017; Badin et al., 2016a; Smith et al., 2016b), future research may wish to investigate differences in response to mental fatigue. Martin et al., (2016) demonstrated a greater resistance to mental fatigue and preservation of physical performance in elite cyclists compared to recreational counterparts. It may be possible that due to the frequent exposure to seemingly cognitively demanding tasks (frequent tactical meetings, travel and match-play), elite football players are more resilient to mental fatigue than non-elite populations. Such speculation however requires further research.

Next, the impact of mental fatigue using ecologically valid protocols is critical in subsequent research. Team meetings have shown to be perceived as long and tiring in elite female football (chapter 8), and future research is required to investigate the impact of prolonged listening, intake of information and coach behaviour on mental fatigue and subsequent football-specific performance. Furthermore, coach travel is commonplace in English football when travelling to away matches, and long journeys (particularly in academy age players who typically arrive to a match within a couple of hours before kick-off, as reported by elite academy players in chapter 7) and their impact on mental fatigue warrants further investigation. Also of interest for future research is the optimal duration necessary to rest from mentally fatiguing tasks. In chapter 5 it was demonstrated that even a 5-min break significantly reduced subjective feelings of mental fatigue, albeit not returning to baseline levels. However, these findings suggested mental fatigue is transient and further work is required to investigate this claim. Finally, further research is required to understand the temporal period of mental fatigue. This thesis has suggested that pre-match mental fatigue is unlikely, and is more likely to occur later in matches and 24 hours post-match.

9.7 - Practical applications

The findings of the thesis provide several practical applications. Firstly, football coaches and practitioners must be made aware of the sources of mental fatigue and its subsequent impact on performance. Therefore, cognitively engaging tasks (i.e. team meetings, media demands, travel) immediately prior to football performance must be adapted to reduce the risk of mental fatigue. In unavoidable situations such as long travel demands, considerations for timing of subsequent training sessions/team meetings is required to ensure optimal readiness to engage. Similar recommendations are provided for post-match recovery, where players are advised to take adequate rest periods before performing in subsequent training sessions (i.e. post-matchday recovery day). Indeed, the aforementioned factors are likely to fluctuate throughout a season, and it is advised that practitioners include mental fatigue as a component of a daily wellness questionnaire in order to elucidate time points in which mental fatigue is present. To reduce feelings of mental fatigue, caffeine has been shown to be an effective substance which can be ingested pre-match or in regular boluses during a match.

10 – THESIS SUMMARY

Mental fatigue in football research has shown to be detrimental on physical, tactical, technical and decision-making performance (Coutinho et al., 2018; Coutinho et al., 2017; Smith et al., 2017; Badin et al., 2016; Smith et al., 2016a; Smith et al., 2016b). The methodologies of these previous studies were examined in chapter 4 of the current thesis for several factors, predominantly the use of the modified Stroop task as a method of inducing mental fatigue in a football-specific cohort, and the inclusion of either recreational/sub-elite players. For future research progress, it was imperative to understand of impact of mental fatigue on elite level players and understand real-life cognitive demands experienced in football and lifestyle activities. Therefore, the aims of the thesis were to subsequently challenge the relevance of the modified Stroop task in mental fatigue in research, and to then use a mixed method approach (surveys and focus groups) to understand the prevalence of mental fatigue in elite football from players from various (domestic, academy and international) demographics. Chapter 5 demonstrated that a 30-min modified Stroop task induces greater subjective boredom compared to a control group, and that a 5-min rest was not enough time to provide a full subjective recovery (i.e. returning to baseline levels) from mentally fatiguing tasks. In chapter 6, a survey with professional male players revealed that many tasks performed are frequent and short in duration (team meetings, driving to training, receiving tactical information pre-match), with a low subjective impact on mental fatigue and performance. A further survey completed by elite academy players (chapter 7) provided similar results, with the inclusion of education providing minimal impact on mental fatigue and performance. In the final study (chapter 8), elite female players cited the impact of prolonged team meetings, the inability to switch off from football-related activity and long-haul travel as causes of mental fatigue. These findings show the variability in perceptions of mental fatigue in football players which likely differs between populations. Future research can benefit from the findings of this thesis in creating mentally fatiguing protocols with greater ecological validity than the currently used modified Stroop task, and provides practitioners with suggestions on how to reduce the impact of mental fatigue in applied settings.

10.1 - Take home messages

- The modified Stroop task has low ecological validity in football as it fails to represent the greater dynamic complexity of football match-play.
- Several pre-match activities (listening to music, watching videos, using smartphone apps) are commonplace in elite football. Many are brief and frequently performed with a low subjective impact of mental fatigue.
- Activities consisting of a greater duration (e.g. team meetings, international travel) increase the risk of mental fatigue.
- Prevalence of mental fatigue in various scenarios is also dependent on gender and competitive level.
- Mental fatigue is a transient state which can be counteracted with rest or caffeine.
- The prevalence of mental fatigue in football is not as widespread and problematic as previously suggested in the literature.

References

Abt, G. A., Dickson, G., & Mummery, W. K. (2001). 16 Goal Scoring Patterns Over the Course of a Match: An Analysis of the Australian National Soccer League. *Science and football IV*, *4*, 106.

Aghajani, H., Garbey, M., & Omurtag, A. (2017). Measuring mental workload with EEG+ fNIRS. *Frontiers in Human Neuroscience*, *11*, 359.

Ahn, S., Nguyen, T., Jang, H., Kim, J. G., & Jun, S. C. (2016). Exploring neuro-physiological correlates of drivers' mental fatigue caused by sleep deprivation using simultaneous EEG, ECG, and fNIRS data. *Frontiers in Human Neuroscience*, *10*, 219.

Åkerstedt, T., Knutsson, A., Westerholm, P., Theorell, T., Alfredsson, L., & Kecklund, G. (2004). Mental fatigue, work and sleep. *Journal of Psychosomatic Research*, *57*(5), 427-433.

Aliyari, H., Kazemi, M., Tekieh, E., Salehi, M., Sahraei, H., Daliri, M. R., ... & Hadipour, M. M. (2015). The effects of FIFA 2015 computer games on changes in cognitive, Hormonal and brain waves functions of young men volunteers. *Basic and Clinical Neuroscience*, *6*(3), 193.

Arazi H, Asadi A, Purabed M. Physiological and psychophysical responses to listening to music during warm-up and circuit-type resistance exercise in strength trained men. Journal of Sports Medicine. 2015;2015.

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. *Annual Review of Neuroscience*, *28*, 403.

Aston-Jones, G., Rajkowski, J., & Cohen, J. (1999). Role of locus coeruleus in attention and behavioral flexibility. *Biological Psychiatry*, *46*(9), 1309-1320.

Azevedo, R., Silva-Cavalcante, M. D., Gualano, B., Lima-Silva, A. E., & Bertuzzi, R. (2016). Effects of caffeine ingestion on endurance performance in mentally fatigued individuals. *European Journal of Applied Physiology*, *116*(11-12), 2293-2303.

Badin, O. O., Smith, M. R., Conte, D., & Coutts, A. J. (2016). Mental fatigue: impairment of technical performance in small-sided soccer games. *International Journal of Sports Physiology and Performance*, *11*(8), 1100-1105.

Banich, M. T., & Depue, B. E. (2015). Recent advances in understanding neural systems that support inhibitory control. *Current Opinion in Behavioral Sciences*, *1*, 17-22.

Barrett, S., McLaren, S., Spears, I., Ward, P., & Weston, M. (2018). The Influence of Playing Position and Contextual Factors on Soccer Players' Match Differential Ratings of Perceived Exertion: A Preliminary Investigation. *Sports*, *6*(1), 13.

Barry, R. J., Rushby, J. A., Wallace, M. J., Clarke, A. R., Johnstone, S. J., & Zlojutro, I. (2005). Caffeine effects on resting-state arousal., *Clinical Neurophysiology*, *116*(11), 2693-2700.

Baumeister, J., Reinecke, K., Cordes, M., Lerch, C., & Weiß, M. (2010). Brain activity in goal-directed movements in a real compared to a virtual environment using the Nintendo Wii. *Neuroscience Letters*, *481*(1), 47-50.

Baumeister, J., Reinecke, K., Liesen, H., & Weiss, M. (2008). Cortical activity of skilled performance in a complex sports related motor task. *European Journal of Applied Physiology*, *104*(4), 625.

Baumeister, J., Reinecke, K., Schubert, M., Schade, J., & Weiss, M. (2012). Effects of induced fatigue on brain activity during sensorimotor control. *European Journal of Applied Physiology*, *112*(7), 2475-2482.

Bengtsson, H., Ekstrand, J., & Hägglund, M. (2013). Muscle injury rates in professional football increase with fixture congestion: an 11-year follow-up of the UEFA Champions League injury study. *British Journal of Sports Medicine*, *47*(12), 743-747.

Berka, C., Levendowski, D. J., Cvetinovic, M. M., Petrovic, M. M., Davis, G., Lumicao, M. N., ... & Olmstead, R. (2004). Real-time analysis of EEG indexes of alertness, cognition, and memory acquired with a wireless EEG headset. *International Journal of Human-Computer Interaction*, *17*(2), 151-170.

Berka, C., Levendowski, D. J., Lumicao, M. N., Yau, A., Davis, G., Zivkovic, V. T., ... & Craven, P. L. (2007). EEG correlates of task engagement and mental workload in vigilance, learning, and memory tasks. *Aviation, space, and environmental medicine*, *78*(5), B231-B244.

Bishop, D. T., Wright, M. J., & Karageorghis, C. I. (2014). Tempo and intensity of pre-task music modulate neural activity during reactive task performance. *Psychology of Music*, *42*(5), 714-727.

Blasi, G., Goldberg, T. E., Weickert, T., Das, S., Kohn, P., Zoltick, B., ... & Mattay, V. S. (2006). Brain regions underlying response inhibition and interference monitoring and suppression. *European Journal of Neuroscience*, *23*(6), 1658-1664.

Boksem, M. A., Meijman, T. F., & Lorist, M. M. (2005). Effects of mental fatigue on attention: an ERP study. *Cognitive Brain Research*, *25*(1), 107-116.

Boksem, M. A., & Tops, M. (2008). Mental fatigue: costs and benefits. *Brain Research Reviews*, *59*(1), 125-139.

Borghini, G., Astolfi, L., Vecchiato, G., Mattia, D., & Babiloni, F. (2014). Measuring neurophysiological signals in aircraft pilots and car drivers for the assessment of mental workload, fatigue and drowsiness. *Neuroscience & Biobehavioral Reviews*, *44*, 58-75.

Bray, S. R., Graham, J. D., Ginis, K. A. M., & Hicks, A. L. (2011). Cognitive task performance causes impaired maximum force production in human hand flexor muscles. *Biological Psychology*, *89*(1), 195-200.

Bray, S. R., Martin Ginis, K. A., Hicks, A. L., & Woodgate, J. (2008). Effects of self-regulatory strength depletion on muscular performance and EMG activation. *Psychophysiology*, *45*(2), 337-343.

Britton J. (2008). Adult EEG. *Clinical Neurophysiology*. 31, 76.

Brown, D. M., & Bray, S. R. (2017). Effects of mental fatigue on physical endurance performance and muscle activation are attenuated by monetary incentives. *Journal of Sport and Exercise Psychology*, *39*(6), 385-396.

Brownsberger, J., Edwards, A., Crowther, R., & Cottrell, D. (2013). Impact of mental fatigue on self-paced exercise. *International Journal of Sports Medicine*, *34*(12), 1029-1036.

Buchheit, M., Racinais, S., Bilsborough, J. C., Bourdon, P. C., Voss, S. C., Hocking, J., ... & Coutts, A. J. (2013). Monitoring fitness, fatigue and running performance during a pre-season training camp in elite football players. *Journal of Science and Medicine in Sport*, *16*(6), 550-555.

Chaudhuri, A., & Behan, P. O. (2004). Fatigue in neurological disorders. *The Lancet*, *363*(9413), 978-988.

Carling, C., & Dupont, G. (2011). Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play?. *Journal of Sports Sciences*, *29*(1), 63-71.

Carling, C., Lacome, M., McCall, A., Dupont, G., Le Gall, F., Simpson, B., & Buchheit, M. (2018). Monitoring of post-match fatigue in professional soccer: welcome to the real-world. *Sports Medicine*, *48*(12), 2695-2702.

Carling, C., McCall, A., Le Gall, F., & Dupont, G. (2016). The impact of short periods of match congestion on injury risk and patterns in an elite football club. *British Journal of Sports Medicine*, *50*(12), 764.

Coutinho, D., Gonçalves, B., Travassos, B., Wong, D. P., Coutts, A. J., & Sampaio, J. E. (2017). Mental fatigue and spatial references impair soccer players' physical and tactical performances. *Frontiers in Psychology*, *8*, 1645.

Coutinho, D., Gonçalves, B., Wong, D. P., Travassos, B., Coutts, A. J., & Sampaio, J. (2018). Exploring the effects of mental and muscular fatigue in soccer players' performance. *Human Movement Science*, *58*, 287-296.

Coutts, A. J. (2016). Fatigue in football: it's not a brainless task!. *Journal of Sports Sciences*, *34*(14), 1296.

Davis, J. M., Zhao, Z., Stock, H. S., Mehl, K. A., Buggy, J., & Hand, G. A. (2003). Central nervous system effects of caffeine and adenosine on fatigue. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *284*(2), R399-R404.

Dellal, A., Lago-Peñas, C., Rey, E., Chamari, K., & Orhant, E. (2015). The effects of a congested fixture period on physical performance, technical activity and injury rate during matches in a professional soccer team. *British Journal of Sports Medicine*, *49*(6), 390-394.

Dillard, M. B., Warm, J. S., Funke, G. J., Funke, M. E., Finomore Jr, V. S., Matthews, G., ... & Parasuraman, R. (2014). The sustained attention to response task (SART) does not promote mindlessness during vigilance performance. *Human Factors*, *56*(8), 1364-1379.

Dupont, G., Nedelec, M., McCall, A., McCormack, D., Berthoin, S., & Wisløff, U. (2010). Effect of 2 soccer matches in a week on physical performance and injury rate. *The American Journal of Sports Medicine*, *38*(9), 1752-1758.

Einöther, S. J., Martens, V. E., Rycroft, J. A., & De Bruin, E. A. (2010). L-theanine and caffeine improve task switching but not intersensory attention or subjective alertness. *Appetite*, *54*(2), 406-409.

Faber, L. G., Maurits, N. M., & Lorist, M. M. (2012). Mental fatigue affects visual selective attention. *PLoS ONE*, *7*(10), e48073.

Fallahi, M., Motamedzade, M., Heidarimoghadam, R., Soltanian, A. R., & Miyake, S. (2016). Effects of mental workload on physiological and subjective responses during traffic density monitoring: a field study. *Applied Ergonomics*, *52*, 95-103.

Fanchini, M., Ferraresi, I., Petruolo, A., Azzalin, A., Ghielmetti, R., Schena, F., & Impellizzeri, F. M. (2017). Is a retrospective RPE appropriate in soccer? Response shift and recall bias. *Science and Medicine in Football*, *1*(1), 53-59.

Fessi, M. S., Nouira, S., Dellal, A., Owen, A., Elloumi, M., & Moalla, W. (2016). Changes of the psychophysical state and feeling of wellness of professional soccer players during pre-season and in-season periods. *Research in Sports Medicine*, *24*(4), 375-386.

Folgado, H., Duarte, R., Marques, P., & Sampaio, J. (2015). The effects of congested fixtures period on tactical and physical performance in elite football. *Journal of Sports Sciences*, *33*(12), 1238-1247.

Fortes, L. S., Lima-Junior, D., Nascimento-Júnior, J. R., Costa, E. C., Matta, M. O., & Ferreira, M. E. (2019). Effect of exposure time to smartphone apps on passing decision-making in male soccer athletes. *Psychology of Sport and Exercise*, *44*, 35-41.

Foskett, A., Ali, A., & Gant, N. (2009). Caffeine enhances cognitive function and skill performance during simulated soccer activity. *International Journal of Sport Nutrition and Exercise Metabolism*, *19*(4), 410-423.

Fowler, P. M., McCall, A., Jones, M., & Duffield, R. (2017). Effects of long-haul transmeridian travel on player preparedness: case study of a national team at the 2014 FIFA World Cup. *Journal of Science and Medicine in Sport*, *20*(4), 322-327.

Fredholm, B. B. (1995). Adenosine, adenosine receptors and the actions of caffeine. *Pharmacology & Toxicology*, *76*(2), 93-101.

Fullagar, H. H., Duffield, R., Skorski, S., White, D., Bloomfield, J., Kölling, S., & Meyer, T. (2016b). Sleep, travel, and recovery responses of national footballers during and after long-haul international air travel. *International Journal of Sports Physiology and Performance*, *11*(1), 86-95.

Fullagar, H., Skorski, S., Duffield, R., & Meyer, T. (2016a). The effect of an acute sleep hygiene strategy following a late-night soccer match on recovery of players. *Chronobiology International*, *33*(5), 490-505.

Garde, A., Laursen, B., Jørgensen, A., & Jensen, B. (2002). Effects of mental and physical demands on heart rate variability during computer work. *European Journal of Applied Physiology*, *87*(4-5), 456-461.

Gao, Y., Pan, B., Li, K., & Li, T. (2016, March). Shed a light in fatigue detection with near-infrared spectroscopy during long-lasting driving. In *Clinical and Translational Neurophotonics; Neural Imaging and Sensing; and Optogenetics and Optical Manipulation* (Vol. 9690).

Geldreich, E. W. (1941). Studies of the galvanic skin response as a deception indicator. *Transactions of the Kansas Academy of Science*, *44*, 346-351.

Gevins, A., Smith, M. E., Leong, H., McEvoy, L., Whitfield, S., Du, R., & Rush, G. (1998). Monitoring working memory load during computer-based tasks with EEG pattern recognition methods. *Human Factors*, *40*(1), 79-91.

Grandjean, E. (1979). Fatigue in industry. *Occupational and Environmental Medicine*, *36*(3), 175-186.

Greco, G., Tambolini, R., Ambruosi, P., & Fischetti, F. (2017). Negative effects of smartphone use on physical and technical performance of young footballers. *Journal of Physical Education and Sport*, *17*(4), 2495-2501.

Hankins, T. C., & Wilson, G. F. (1998). A comparison of heart rate, eye activity, EEG and subjective measures of pilot mental workload during flight. *Aviation, Space, and Environmental Medicine*, *69*(4), 360-367.

Hockey, G. R. J. (2011). A motivational control theory of cognitive fatigue. *Cognitive fatigue: Multidisciplinary Perspectives on Current Research and Future Applications*, 167-87.

Hjortskov, N., Rissén, D., Blangsted, A. K., Fallentin, N., Lundberg, U., & Søgaard, K. (2004). The effect of mental stress on heart rate variability and blood pressure during computer work. *European Journal of Applied Physiology*, *92*(1-2), 84-89.

Horvath, F. (1979). Effect of different motivational instructions on detection of deception with the psychological stress evaluator and the galvanic skin response. *Journal of Applied Psychology*, *64*(3), 323.

Hoshi, Y. (2003). Functional near-infrared optical imaging: Utility and limitations in human brain mapping. *Psychophysiology*, *40*(4), 511-520.

Jacobson, B. H., & Edgley, B. M. (1987). Effects of caffeine on simple reaction time and movement time. *Aviation, Space, and Environmental Medicine*, *58*(12), 1153-1156.

Johnson, S. K., DeLuca, J., & Natelson, B. H. (1996). Personality dimensions in the chronic fatigue syndrome: a comparison with multiple sclerosis and depression. *Journal of Psychiatric Research*, *30*(1), 9-20.

Judelson, D. A., Armstrong, L. E., Sökmen, B., Roti, M. W., Casa, D. J., & Kellogg, M. D. (2005). Effect of chronic caffeine intake on choice reaction time, mood, and visual vigilance. *Physiology & Behavior*, *85*(5), 629-634.

Kato, Y., Endo, H., & Kizuka, T. (2009). Mental fatigue and impaired response processes: event-related brain potentials in a Go/NoGo task. *International Journal of Psychophysiology*, *72*(2), 204-211.

Kida, N., Oda, S., & Matsumura, M. (2005). Intensive baseball practice improves the Go/Nogo reaction time, but not the simple reaction time. *Cognitive Brain Research*, *22*(2), 257-264.

Lal, S. K., & Craig, A. (2002). Driver fatigue: electroencephalography and psychological assessment. *Psychophysiology*, *39*(3), 313-321.

Lambooij, M., Fortuin, M., Heynderickx, I., & IJsselsteijn, W. (2009). Visual discomfort and visual fatigue of stereoscopic displays: A review. *Journal of Imaging Science and Technology*, *53*(3), 30201-1.

Laukka, P., & Quick, L. (2013). Emotional and motivational uses of music in sports and exercise: a questionnaire study among athletes. *Psychology of Music*, *41*(2), 198-215.

LeDuc, P. A., Greig, J. L., & Dumond, S. L. (2005). Involuntary eye responses as measures of fatigue in US Army Apache aviators. *Aviation, Space, and Environmental Medicine*, *76*(7), C86-C91.

Le Mansec, Y., Seve, C., & Jubeau, M. (2017). Neuromuscular fatigue and time motion analysis during a table tennis competition. *The Journal of Sports Medicine and Physical Fitness*, *57*(4), 353.

Lee, K. A., Hicks, G., & Nino-Murcia, G. (1991). Validity and reliability of a scale to assess fatigue. *Psychiatry Research*, *36*(3), 291-298.

Lelis-Torres, N., Ugrinowitsch, H., Apolinário-Souza, T., Benda, R. N., & Lage, G. M. (2017). Task engagement and mental workload involved in variation and repetition of a motor skill. *Scientific Reports*, *7*(1), 14764.

Lopez-Garcia, P., Lesh, T. A., Salo, T., Barch, D. M., MacDonald, A. W., Gold, J. M., ... & Carter, C. S. (2016). The neural circuitry supporting goal maintenance during cognitive control: a comparison of expectancy AX-CPT and dot probe expectancy paradigms. *Cognitive, Affective, & Behavioral Neuroscience*, *16*(1), 164-175.

Lorist, M. M., Boksem, M. A., & Ridderinkhof, K. R. (2005). Impaired cognitive control and reduced cingulate activity during mental fatigue. *Cognitive Brain Research*, *24*(2), 199-205.

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science*, *288*(5472), 1835-1838.

MacMahon, C., Hawkins, Z., & Schücker, L. (2019). Beep Test Performance Is Influenced by 30 Minutes of Cognitive Work. *Medicine and Science in Sports and Exercise*, 1-29.

MacMahon, C., Schücker, L., Hagemann, N., & Strauss, B. (2014). Cognitive fatigue effects on physical performance during running. *Journal of Sport and Exercise Psychology*, *36*(4), 375-381.

Magnusson, A. E., Nias, D. K. B., & White, P. D. (1996). Is perfectionism associated with fatigue? *Journal of Psychosomatic Research*, *41*(4), 377-383.

Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *Journal of Applied Physiology*, *106*(3), 857-864.

Marcora, S. M., Staiano, W., & Merlini, M. (2015). A randomized controlled trial of brain endurance training (bet) to reduce fatigue during endurance exercise. *Medicine & Science in Sports & Exercise*, *47*(5S), 198.

Martin, K., Meeusen, R., Thompson, K. G., Keegan, R., & Rattray, B. (2018). Mental fatigue impairs endurance performance: a physiological explanation. *Sports Medicine*, 1-11.

Martin, K., Staiano, W., Menaspà, P., Hennessey, T., Marcora, S., Keegan, R., ... & Rattray, B. (2016). Superior inhibitory control and resistance to mental fatigue in professional road cyclists. *PloS One*, *11*(7), e0159907.

Martin, K., Thompson, K. G., Keegan, R., Ball, N., & Rattray, B. (2015). Mental fatigue does not affect maximal anaerobic exercise performance. *European Journal of Applied Physiology*, *115*(4), 715-725.

McEvoy, L. K., Smith, M. E., & Gevins, A. (2000). Test–retest reliability of cognitive EEG. *Clinical Neurophysiology*, *111*(3), 457-463.

McEwen, B. S., & Sapolsky, R. M. (1995). Stress and cognitive function. *Current opinion in neurobiology*, *5*(2), 205-216.

McGarrigle, R., Dawes, P., Stewart, A. J., Kuchinsky, S. E., & Munro, K. J. (2017). Pupillometry reveals changes in physiological arousal during a sustained listening task. *Psychophysiology*, *54*(2), 193-203.

McMorris, T., Barwood, M., Hale, B. J., Dicks, M., & Corbett, J. (2018). Cognitive fatigue effects on physical performance: a systematic review and meta-analysis. *Physiology & Behavior*, *188*, 103-107.

Menon, V., Adleman, N. E., White, C. D., Glover, G. H., & Reiss, A. L. (2001). Error-related brain activation during a Go/NoGo response inhibition task. *Human Brain Mapping*, *12*(3), 131-143.

Mehta, R. K., Ayaz, H., McKendrick, R., Izzetoglu, K., Willems, B., & Ziegler, M. (2016, September). Is Functional Near Infrared Spectroscopy (fNIRS) Appropriate for your Research?. In *Proceedings of the*

Human Factors and Ergonomics Society Annual Meeting (Vol. 60, No. 1, pp. 188-190). Sage CA: Los Angeles, CA: SAGE Publications.

Mehta, R. K., & Parasuraman, R. (2014). Effects of mental fatigue on the development of physical fatigue: a neuroergonomic approach. *Human Factors*, *56*(4), 645-656.

Millward, P. (2017). A whole new ball game: The English Premier League and television broadcast rights. In *The English Premier League* (pp. 33-48). Routledge.

Moore, T. M., Key, A. P., Thelen, A., & Hornsby, B. W. (2017). Neural mechanisms of mental fatigue elicited by sustained auditory processing. *Neuropsychologia*, *106*, 371-382.

Morad, Y., Barkana, Y., Zadok, D., Hartstein, M., Pras, E., & Bar-Dayan, Y. (2009). Ocular parameters as an objective tool for the assessment of truck drivers fatigue. *Accident Analysis & Prevention*, *41*(4), 856-860.

Moreira, A., Aoki, M. S., Franchini, E., da Silva Machado, D. G., Paludo, A. C., & Okano, A. H. (2018). Mental fatigue impairs technical performance and alters neuroendocrine and autonomic responses in elite young basketball players. *Physiology & Behavior*, *196*, 112-118.

Mosso, A. (1891). La Fatica. Milano, Italy, Treves.

Nall, A. H., Shakhmantsir, I., Cichewicz, K., Birman, S., Hirsh, J., & Sehgal, A. (2016). Caffeine promotes wakefulness via dopamine signaling in Drosophila. *Scientific Reports*, *6*, 20938.

Nieoullon, A. (2002). Dopamine and the regulation of cognition and attention. *Progress in Neurobiology*, *67*(1), 53-83.

Nieuwenhuis, S., Aston-Jones, G., & Cohen, J. D. (2005). Decision making, the P3, and the locus coeruleus--norepinephrine system. *Psychological Bulletin*, *131*(4), 510.

Nguyen, T., Ahn, S., Jang, H., Jun, S. C., & Kim, J. G. (2017). Utilization of a combined EEG/NIRS system to predict driver drowsiness. *Scientific Reports*, *7*, 43933.

Noon, M. R., James, R. S., Clarke, N. D., Akubat, I., & Thake, C. D. (2015). Perceptions of well-being and physical performance in English elite youth footballers across a season. *Journal of Sports Sciences*, *33*(20), 2106-2115.

Nourbakhsh, N., Chen, F., Wang, Y., & Calvo, R. A. (2017). Detecting users' cognitive load by galvanic skin response with affective interference. *ACM Transactions on Interactive Intelligent Systems (TiiS)*, *7*(3), 12.

Okogbaa, O. G., Shell, R. L., & Filipusic, D. (1994). On the investigation of the neurophysiological correlates of knowledge worker mental fatigue using the EEG signal., *Applied Ergonomics*, *25*(6), 355-365.

Pageaux, B., Lepers, R., Dietz, K. C., & Marcora, S. M. (2014). Response inhibition impairs subsequent self-paced endurance performance. *European Journal of Applied Physiology*, *114*(5), 1095-1105.

Pageaux, B., Marcora, S. M., & Lepers, R. (2013). Prolonged mental exertion does not alter neuromuscular function of the knee extensors. *Medicine and Science in Sports and Exercise*, *45*(12), 2254.

Pageaux, B., Marcora, S. M., Rozand, V., & Lepers, R. (2015). Mental fatigue induced by prolonged self-regulation does not exacerbate central fatigue during subsequent whole-body endurance exercise. *Frontiers in Human Neuroscience*, *9*, 67.

Pain, M. A., Harwood, C., & Anderson, R. (2011). Pre-competition imagery and music: The impact on flow and performance in competitive soccer. *The Sport Psychologist*, *25*(2), 212-232.

Park, J., Kim, Y., Chung, H. K., & Hisanaga, N. (2001). Long working hours and subjective fatigue symptoms. *Industrial Health*, *39*(3), 250-254.

Pattyn, N., Neyt, X., Henderickx, D., & Soetens, E. (2008). Psychophysiological investigation of vigilance decrement: Boredom or cognitive fatigue? *Physiology & Behavior*, *93*, 369-378.

Pelletier, C. L. (2004). The effect of music on decreasing arousal due to stress: A meta-analysis. *Journal of Music Therapy*, *41*(3), 192-214.

Penna, E. M., Filho, E., Wanner, S. P., Campos, B. T., Quinan, G. R., Mendes, T. T., ... & Prado, L. S. (2018). Mental Fatigue Impairs Physical Performance in Young Swimmers. *Pediatric exercise science*, *30*(2), 208-215.

Pires, F. O., Silva-Júnior, F. L., Brietzke, C., Franco-Alvarenga, P. E., Pinheiro, F. A., de França, N. M., ... & Meireles Santos, T. (2018). Mental fatigue alters cortical activation and psychological responses, impairing performance in a distance-based cycling trial., *Frontiers in Physiology*, *9*, 227.

Prins, J.B., van der Meer, J.W., Bleijenberg, G. (2006). Chronic fatigue syndrome. *The Lancet*, 367, 346–55.

Quinlan, P., Lane, J., & Aspinall, L. (1997). Effects of hot tea, coffee and water ingestion on physiological responses and mood: the role of caffeine, water and beverage type. *Psychopharmacology*, *134*(2), 164-173.

Raab, M., & Laborde, S. (2011). When to blink and when to think: preference for intuitive decisions results in faster and better tactical choices. *Research Quarterly for Exercise and Sport*, *82*(1), 89-98.

Rampinini, E., Impellizzeri, F. M., Castagna, C., Azzalin, A., Ferrari, D. B., & Wisløff, U. (2008). Effect of match-related fatigue on short-passing ability in young soccer players. *Medicine and science in sports and exercise*, *40*(5), 934-942.

Rampinini, E., Impellizzeri, F. M., Castagna, C., Coutts, A. J., & Wisløff, U. (2009). Technical performance during soccer matches of the Italian Serie A league: Effect of fatigue and competitive level. *Journal of Science and Medicine in Sport*, *12*(1), 227-233.

Reinecke, K., Cordes, M., Lerch, C., Koutsandréou, F., Schubert, M., Weiss, M., & Baumeister, J. (2011). From lab to field conditions: a pilot study on EEG methodology in applied sports sciences. *Applied Psychophysiology and Biofeedback*, *36*(4), 265-271.

Rozand, V., Pageaux, B., Marcora, S. M., Papaxanthis, C., & Lepers, R. (2014). Does mental exertion alter maximal muscle activation? *Frontiers in Human Neuroscience*, *8*, 755.

Russoniello, C. V., O'Brien, K., & Parks, J. M. (2009). The effectiveness of casual video games in improving mood and decreasing stress. *Journal of CyberTherapy & Rehabilitation*, *2*(1), 53-66.

Salam, H., Marcora, S. M., & Hopker, J. G. (2018). The effect of mental fatigue on critical power during cycling exercise. *European Journal of Applied Physiology*, *118*(1), 85-92.

Sampei, K., Ogawa, M., Torres, C. C. C., Sato, M., & Miki, N. (2016). Mental fatigue monitoring using a wearable transparent eye detection system. *Micromachines*, *7*(2), 20.

Sheppard, J. M., & Young, W. B. (2006). Agility literature review: Classifications, training and testing. *Journal of Sports Sciences*, *24*(9), 919-932.

Silva-Júnior, F., Emanuel, P., Sousa, J., Silva, M., Teixeira, S., Pires, F. O., ... & Arias-Carrion, O. (2016). Prior Acute Mental Exertion in Exercise and Sport. *Clinical Practice and Epidemiology in Mental Health*, *12*, 94-107.

Slimani, M., Znazen, H., Bragazzi, N., Zguira, M., & Tod, D. (2018). The Effect of Mental Fatigue on Cognitive and Aerobic Performance in Adolescent Active Endurance Athletes: Insights from a Randomized Counterbalanced, Cross-Over Trial., *Journal of Clinical Medicine*, *7*(12), 510.

Smith, M. R., Coutts, A. J., Merlini, M., Deprez, D., Lenoir, M., & Marcora, S. M. (2016). Mental fatigue impairs soccer-specific physical and technical performance. *Medicine & Science in Sports & Exercise*, *48*(2), 267-276.

Smith, M. R., Fransen, J., Deprez, D., Lenoir, M., & Coutts, A. J. (2017). Impact of mental fatigue on speed and accuracy components of soccer-specific skills. *Science and Medicine in Football*, *1*(1), 48-52.

Smith, M. R., Marcora, S. M., & Coutts, A. J. (2015). Mental fatigue impairs intermittent running performance. *Medicine and Science in Sports and Exercise*, *47*(8), 1682.

Smith, M. R., Thompson, C., Marcora, S. M., Skorski, S., Meyer, T., & Coutts, A. J. (2018). Mental fatigue and soccer: Current knowledge and future directions. *Sports Medicine*, 1-8.

Smith, M. R., Zeuwts, L., Lenoir, M., Hens, N., De Jong, L. M., & Coutts, A. J. (2016). Mental fatigue impairs soccer-specific decision-making skill. *Journal of Sports Sciences*, *34*(14), 1297-1304.

Sparks, K., Cooper, C., Fried, Y., & Shirom, A. (1997). The effects of hours of work on health: a meta-analytic review. *Journal of Occupational and Organizational Psychology*, *70*(4), 391-408.

Stahl, S. M. (2002). Neurotransmission of cognition, part 1. Dopamine is a hitchhiker in frontal cortex: norepinephrine transporters regulate dopamine. *Journal of Clinical Psychiatry*, *64*(1), 4-5.

Stratton, V. N., & Zalanowski, A. H. (1984). The relationship between music, degree of liking, and self-reported relaxation. *Journal of Music Therapy*, *21*(4), 184-192.

Suzuki, M., Umeda, T., Nakaji, S., Shimoyama, T., Mashiko, T., & Sugawara, K. (2004). Effect of incorporating low intensity exercise into the recovery period after a rugby match. *British Journal of Sports Medicine*, *38*(4), 436-440.

Taelman, J., Vandeput, S., Vlemincx, E., Spaepen, A., & Van Huffel, S. (2011). Instantaneous changes in heart rate regulation due to mental load in simulated office work. *European Journal of Applied Physiology*, *111*(7), 1497-1505.

Teplan, M. (2002). Fundamentals of EEG measurement. *Measurement Science Review*, *2*(2), 1-11.

Terry, P. C., Lane, A. M., & Fogarty, G. J. (2003). Construct validity of the Profile of Mood States—Adolescents for use with adults. *Psychology of Sport and Exercise*, *4*(2), 125-139.

Thompson, C. J., Fransen, J., Skorski, S., Smith, M. R., Meyer, T., Barrett, S., & Coutts, A. J. (2018). Mental fatigue in football: is it time to shift the goalposts? An evaluation of the current methodology. *Sports Medicine*, 1-7.

Ting, P. H., Hwang, J. R., Doong, J. L., & Jeng, M. C. (2008). Driver fatigue and highway driving: A simulator study. *Physiology & Behavior*, *94*(3), 448-453.

van Cutsem, J., De Pauw, K., Marcora, S., Meeusen, R., & Roelands, B. (2018). A caffeine-maltodextrin mouth rinse counters mental fatigue. *Psychopharmacology*, *235*(4), 947-958.

van Cutsem, J., Marcora, S., De Pauw, K., Bailey, S., Meeusen, R., & Roelands, B. (2017). The effects of mental fatigue on physical performance: a systematic review. *Sports Medicine*, *47*(8), 1569-1588.

van der Linden, D. (2011). The urge to stop: The cognitive and biological nature of acute mental fatigue. *Cognitive fatigue: Multidisciplinary perspectives on current research and future applications*, 149-64.

van der Linden, D., Frese, M., & Meijman, T. F. (2003). Mental fatigue and the control of cognitive processes: effects on perseveration and planning. *Acta Psychologica*, *113*(1), 45-65.

Veness, D., Patterson, S. D., Jeffries, O., & Waldron, M. (2017). The effects of mental fatigue on cricket-relevant performance among elite players. *Journal of Sports Sciences*, *35*(24), 2461-2467.

Vickery, W., Duffield, R., Crowther, R., Beakley, D., Blanch, P., & Dascombe, B. J. (2018). Comparison of the physical and technical demands of cricket players during training and match-play. *The Journal of Strength & Conditioning Research*, *32*(3), 821-829.

Volkow, N. D., Wang, G. J., Logan, J., Alexoff, D., Fowler, J. S., Thanos, P. K., ... & Tomasi, D. (2015). Caffeine increases striatal dopamine D 2/D 3 receptor availability in the human brain. *Translational Psychiatry*, *5*(4), e549.

Vrijkotte, S., Meeusen, R., Vandervaeren, C., Buyse, L., Cutsem, J. V., Pattyn, N., & Roelands, B. (2018). Mental Fatigue and Physical and Cognitive Performance During a 2-Bout Exercise Test. *International Journal of Sports Physiology and Performance*, *13*(4), 510-516.

Walsh, V. (2014). Is sport the brain's biggest challenge?. *Current Biology*, *24*(18), R859-R860.

Widyanti, A., Muslim, K., & Sutalaksana, I. Z. (2017). The sensitivity of Galvanic Skin Response for assessing mental workload in Indonesia. *Work*, *56*(1), 111-117.

Williams, A. M. (2000). Perceptual skill in soccer: Implications for talent identification and development. *Journal of Sports Sciences*, *18*(9), 737-750.

White, C., & Schweitzer, R. (2000). The role of personality in the development and perpetuation of chronic fatigue syndrome. *Journal of Psychosomatic Research*, *48*(6), 515-524.

Winch, W. H. (1912). Mental fatigue in day school children as measured by immediate memory: Part I. *Journal of Educational Psychology*, *3*(1), 18.

Xu, G., Zhang, M., Wang, Y., Liu, Z., Huo, C., Li, Z., & Huo, M. (2017). Functional connectivity analysis of distracted drivers based on the wavelet phase coherence of functional near-infrared spectroscopy signals. *PLoS One*, *12*(11), e0188329.

Yong, L., Guo'en, Y., & Yanli, C. (2004). The regulating effect of fatigue and mental load on pupil size in text reading. *Studies of Psychology and Behavior*, *3*, B842.

Zhao, C., Zhao, M., Liu, J., & Zheng, C. (2012). Electroencephalogram and electrocardiograph assessment of mental fatigue in a driving simulator. *Accident Analysis & Prevention*, *45*, 83-90.

Curriculum Vitae

Chris Thompson

26 Pebble Walk, Tramore, Co Waterford, Ireland

Tel: +353894849410 Email: cthompson@wit.ie

Personal profile

Lecturer in Sport and Exercise Psychology at Waterford Institute of Technology, Ireland

Applied Sport Science experience with Leicester City, Leicester Tigers, Borussia Dortmund and TSG 1899 Hoffenheim

External research collaborations in England, Ireland, Germany and Australia

Education

2016 – Present **Saarland University, Germany & University of Technology, Sydney, Australia**

PhD in Sport and Exercise Science (Funded by DAAD)

Thesis title: Mental Fatigue in Football

Supervisors – Prof Aaron Coutts, Prof Tim Meyer & Dr Sabrina Skorski

2015 – 2016 **Nottingham Trent University**

PGCert Exercise Physiology

Overall grade – Merit

2010 – 2013 **University of Hull**

BSc Sport and Exercise Science

Overall grade - Upper second-class honours

Dissertation – Barriers to physical activity in young adults

Teaching experience

2019 – present **Lecturer – Waterford Institute of Technology, Ireland**

Teaching

- Organisation and delivery of three modules per semester (Sport Psychology, Exercise Psychology and Skill Acquisition)
- Consisting of 18 hours teaching per week
- This teaching ranges from Year 1 – 4 of the undergraduate courses (Sport and Exercise Science, Health and Exercise Science, Business and Recreation Management)

Supervision

- Supervising four undergraduate dissertation projects in Strength and Conditioning and Psychology related areas

2016 – 2018 **Lecturer in Sport and Exercise Science – Saarland University (Germany)**

Teaching

- Organisation and delivery of the MSc module – "Science in Football"
- Relevant topics include Psychology in Football, Mental Health in Football, and Cognitive Training in Football

Applied work experience

2016 – 2018 **Sport Science support – TSG 1899 Hoffenheim**

- Complete regular psychological testing batteries with academy squads

2016 – 2018 **Sport Scientist – Borussia Dortmund FC**

- Assist in pre-season and winter break fitness testing protocols for first team and academy age squads

2015 - 2016 **Leicester City Football Club – Research Student**

2014 - 2015 **Coventry City FC – Strength and Conditioning intern**

2013 - 2014 **Everyone Active, Oadby, Leicester - Gym instructor**

2013 - 2014 **Leicester Tigers RFC - Full time Strength and Conditioning intern**

2009 - 2010 **Leicester Riders Basketball Club – Strength and Conditioning Coach**

Publications

Thompson, C. J., Noon, M., Towlson, C., Perry, J., Coutts, A. J., Harper, L. D., ... & Meyer, T. (2020). Understanding the presence of mental fatigue in English academy soccer players. *Journal of Sports Sciences*, 1-7.

Herold, M., Goes, F., Nopp, S., Bauer, P., Thompson, C., & Meyer, T. (2019). Machine learning in men's professional football: Current applications and future directions for improving attacking play. *International Journal of Sports Science & Coaching*, *14*(6), 798-817.

Thompson, C. J., Fransen, J., Skorski, S., Smith, M. R., Meyer, T., Barrett, S., & Coutts, A. J. (2018). Mental Fatigue in Football: Is it Time to Shift the Goalposts? An Evaluation of the Current Methodology. *Sports Medicine*, 1-7.

Smith, M. R., Thompson, C., Marcora, S. M., Skorski, S., Meyer, T., & Coutts, A. J. (2018). Mental Fatigue and Soccer: Current Knowledge and Future Directions. *Sports Medicine*, 1-8.

McCunn, R., Thompson, C., Beavan, A., & Gibson, N. (2018). Head in the game: mental fatigue and its potential influence on the perceptual-cognitive element in sport. *The Sport and Exercise Scientist*, *57*, 20-21.

Meyer, T., Julian, R., & Thompson, C. (2018). Exercise Physiology of Football: Factors Related to Performance and Health. In *Return to Play in Football* (pp. 85-95). Springer, Berlin, Heidelberg.

Current research projects

Thompson, C., Towlson, C., Skorski, S., Harper, L., Barrett, S., Coutts, A., & Meyer, T. Understanding the mental demands of elite football players.

Thompson, C., Smith, A., Skorski, S., Datson, N., Barrett, S., Coutts, A., & Meyer, T. Understanding the mental pressures of elite international football – A qualitative study.

Conferences

Thompson, C. Invited Guest Speaker – "Standing out from the crowd. Careers advice for undergraduate students". (March 2018). *Oral presentation presented at the 8th Annual* Student Thesis Conference, Hull, United Kingdom.

Thompson, C., Towlson, C., Skorski, S., Harper, L., Barrett, S., Coutts, A., & Meyer, T. (April 2018) Understanding the mental demands of elite football players. *Oral presentation presented at the 3rd Annual Science and Engineering Conference on Sports Innovation, Groningen, Netherlands*.

Thompson, C., Towlson, C., Skorski, S., Harper, L., Barrett, S., Coutts, A., & Meyer, T. (July 2018). Understanding the mental demands of elite football players. *Oral presentation presented at the 23rd Annual Congress of the European College of Sports Sciences, Dublin, Ireland.*

References

Distinguished Professor Aaron Coutts
University of Technology Sydney
Moore Park Campus
Sydney
Aaron.Coutts@uts.edu.au
+61 2 95145188

Professor Andy Smith
Professor of Sport and Physical Activity
Wilson Centre
Edge Hill University
andy.smith@edgehill.ac.uk
+44(0) 1695 657295

Tag der Promotion: 28. April. 2021

Dekan: Prof. Dr. M. D. Menger

Bericherstatter: Prof. T. Meyer

Prof. H. Flor

Dr. V. Kelly