The link between mental fatigue and physical performance

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List of abbreviations

3MT	3min all-out cycling test
α	Alpha
β	Beta
δ	Delta
γ	Gamma
θ	Theta
A	Age
AG	Angular Gyrus
APFC	Anterior Prefrontal Cortex
AX-CPT	AX-Continuous Performance Test
BAs	Brodmann Areas
[Bla]	Blood lactate
BRUMS	Brunel Mood Scale
C / CON	Control
CAF-MALT	Caffeine-maltodextrin
CMJ	Countermovement Jump
CMSS	Current Mood State Scale
CO	Cardiac Output
CT	Cognitive Task
DA	Dopamine
DLPFC	Dorsolateral Prefrontal Cortex
EEG	Electroencephalography
EMG	Electromyography
ERP	Event-Related Potential
F	Female
FFG	Fusiform Gyrus
FFT	Fast Fourier Transform
fMRI	functional Magnetic Resonance Imaging
fNIRS	functional Near Infrared Spectroscopy
HIA	High-Intensity Activity
HP	Heat Pad
HR	Heart Rate
Hz	Hertz
I / INT	Intervention
ICA	Independent Component Analysis
kg	Kilogram
km	Kilometres
LIA	Low-Intensity Activity
M	Male

m	Meter
MeSH	Medical Subject heading
MF	Mental Fatigue
MFS	Self-reported mental fatigue / mental fatigue-visual analogue scale
min	Minutes
ml	Millimetre
MR	Mouth Rinse-trial
M-VAS	Self-reported mental fatigue / mental fatigue-visual analogue scale
MVC	Maximal Voluntary Contraction
NASA-TLX	National Aeronautics and Space Administration Task Load Index
nRCT	non-Randomized Controlled trial
nRnCT	non-Randomized non-Controlled Trial
OFC	Orbitofrontal Cortex
OR	Odd Ratio
PICOS	Population, Intervention, Comparison, Outcome and Study design
PLAC	Placebo-trial
POMS	Profile of Mood States
PT	Physical Task
r	correlation coefficients
RCT	Randomized controlled trial
ROI	Region Of Interest
RPE	Rating of Perceived Exertion
RPM	Revolutions Per Minute / Pedalling rate
RSME	Rating Scale of Mental Effort
RT	Reaction Time
s	Seconds
SAC	Somatosensory Association Cortex
SD	Standard Deviation
SE	Standard Error
SIMS	Situational Intrinsic Motivation Scale
SSG	Small-Sided-Game
SV	Stroke Volume
t	time
Tcore	Core Temperature / internal body temperature
Tdcomf	Thermal Discomfort
Tsens	Thermal sensation
Tskin	Skin Temperature
TT	Time Trial
TTE	Time To Exhaustion
VAS	Visual Analog Scale

VE	Minute Ventilation
VO2	Oxygen uptake
VO_{2max}	Maximal Aerobic Capacity
W	Watt
WU	Warm-up
Wmax	Maximal Wattage
Wout	workload of the last completed stage
Wpeak	Peak Power Output
Y	Years
Yo-Yo IR1	Yo-Yo intermittent recovery test, level 1

Chapter 1: General introduction

1.1 Fatigue

Fatigue is a very common, multifaceted phenomenon that everybody encounters in their everyday life. In our modern societies it has been reported that 20–30% of the general population in Europe and the United States experience substantial (i.e. requiring a longer time than normal to recover from work-load or resulting in an increase of risk for health-problems) fatigue [1, 2]. We all associate fatigue with the urge to sleep at the end of a busy day, the need for coffee in the morning, the burning sensation in our legs and lungs at the end of an intensive physical workout, the feeling of a much-needed break in the afternoon during a work-day, the problems with staying attentive during a prolonged drive, … . Fatigue can cause substantial limitations in mental, physical and/or social functioning, resulting in considerable social and economic impacts (e.g. increased medical consumption, absenteeism from work). The ubiquitous presence of fatigue in our everyday life has caused the topic of fatigue to sprout in specific research fields such as exercise physiology, cognitive psychology, medicine and engineering. Fatigue being a topic in so many research fields has led to a vast amount of definitions, with a different focus in each area of expertise. It has been defined as an experimental concept, a symptom, a risk, a cause (e.g. of performance decrement) and a consequence (e.g. of sleep deprivation). To a certain extent, this fragmentation of fatigue-definitions can be explained logically, because it is self-evident that from a research point of view there is a necessity to clearly define what one wants to investigate/research. The disadvantage is however that different research lines of fatigue emerge and co-exist without any interaction. Subsequently the possible breakthroughs that this interaction could trigger are missed.

Within sports science, lines of research on fatigue in exercise physiology and psychology could benefit from increased interaction with one another. In exercise physiology research, the main focus has long been on determining the critical threshold that could clarify why people physically fatigue at a certain point and terminate exercise. This resulted in multiple important insights and definitions of fatigue such as peripheral and central fatigue. Peripheral fatigue is usually described as an impairment located in the muscle and characterized by a metabolic end point, while central fatigue is defined as a failure of the central nervous system to adequately drive the muscle [3]. In other words, peripheral fatigue occurs distal to the point of nerve stimulation and central fatigue emerges centrally, from the point of nerve stimulation up to and including the brain. This quest for a critical threshold did however never succeed in pinpointing that one critical threshold. For peripheral fatigue, proposed mechanisms to play an important role are for example impaired calcium release from the sarcoplasmic reticulum [4] and disturbed muscle ionic homeostasis (i.e. intracellular-interstitial perturbations in K^+ and Na^+ concentrations) [5]. Within this concept of peripheral fatigue, it is hypothesized that during exercise, afferent feedback related to this fatigue is provided to various spinal and supraspinal centres by group III and IV fibres [6] and this subsequently limits exercise performance. Given the existence of such sensory system it seems logical that these afferent stimuli play a role in the occurrence of exercise limitation. Nevertheless, the exact extent of the afferent stimuli's role and whether it translates to the concept of a critical threshold is however still open for debate [7-11]. Central fatigue, however, refers to the central nervous system-factors that are thought to play a role in the development of fatigue, spinal and/or supraspinal (i.e. the brain). Similar to the muscle, also in the brain multiple disturbances in homeostasis have been proposed to lead to fatigue [12]. Mechanisms that have been put forward to play a role in central fatigue are for example challenged oxygenation of the brain during exercise [13], biochemical [3], and thermodynamic changes of the cerebral homeostasis [12]. Thomas et al. [14] correctly summarized and argued that adjustments in skeletal muscle (i.e. peripheral), as a consequence of exhaustive exercise, are intensity- and mode-dependent, and not regulated to a critical threshold. In the brain, the exhaustive exercise-induced changes in oxygenation, neurotransmitter concentrations, glycogen availability, … are probably also intensity- and mode-dependent, and not regulated to a critical threshold. Understanding the significance of this web of modulating physiological factors that contribute to fatigue, how they vary with the exercise task, and how the tolerance of fatigue can be modulated by specific interventions remain key questions for our understanding of human performance [14]. Further complicating this search on the mechanisms of fatigue is the fact that human performance is, besides by physiological factors, also determined by psychological factors. McCormick et al. [15] listed several psychological determinants of endurance performance, e.g. self-talk, goal setting, imagery, … and underlined that there is more to human performance than solely physiology. In psychology fatigue is often proposed to result from the aversiveness towards exerting effort to perform work (cognitive and/or physical) [16, 17]. From this perspective, fatigue functions to maintain the motivational balance between maintaining effort to perform on the task at hand versus switching to another task that is more inherently rewarding [16]. In the search to explain fatigue in sports science, an approach combining exercise physiology and psychology might thus prove to be particularly fruitful.

Recently a line of research on mental fatigue emerged that contains aspects of both exercise physiology and psychology and as such might prove to be a valuable asset in the ongoing refocus on fatigue being a continuum rather than a dichotomy (i.e. fatigue is present or not). In sports science, this line of mental fatigue attempts to provide some further insights in the mechanisms behind the underperformance on physical tasks following the execution of a prolonged demanding cognitive task. In attempting to do so, the role of physiological and psychological factors in physical performance is assessed.

1.2 Mental fatigue

1.2.1 Definition and terminology

Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity [18, 19] and can be manifested subjectively, behaviourally and physiologically. Subjectively, increased feelings of tiredness, lack of energy [20] and a decrease in motivation [21] and alertness have been reported [22]. Behaviourally, mental fatigue is recognized as a decline in performance (accuracy and/or reaction time (RT)) on a cognitive task [23-25]. Finally, alterations in brain activity [23, 26-28] have been shown to be a physiological manifestation of mental fatigue. Changes in all three of these areas (subjective, behavioural, and physiological) do not have to be present for mental fatigue to be present. For instance, cognitive performance does not necessarily decline when one is mentally fatigued, since compensatory effort (e.g. indicated by alterations in brain activity or as a result of increased motivation) may alleviate this decrease in cognitive performance [24, 28]. Hopstaken et al. [28] increased motivation near the end of a prolonged cognitively demanding task by providing a monetary incentive and found that cognitive performance declines were reversed, despite previous signs of mental fatigue.

Some haziness exists in regard to the terminology used to indicate the fatigue induced by demanding cognitive activity. Some authors, like Ackerman & Kanfer [29] and MacMahon et al. [30], argued that the typical task used to induce fatigue by a prolonged demanding cognitive task is more appropriately termed cognitive. Therefore, instead of ‘mental fatigue’ these authors used the term ‘cognitive fatigue’. It is our opinion that ‘mental fatigue’ is however more appropriate as it includes emotion and motivation rather than just cognition. The term mental fatigue better encompasses constructs like cognition, sensation and perception and the complex interactions between these constructs. Bray et al. [31-33] and Pageaux et al. [34] labelled the fatigue inducing-cognitive task intervention as a 'self-regulatory depletion manipulation'. Self-regulation refers to the mental abilities that allow people to exert control over their behaviours, thoughts, and emotions to pursue their goals [33, 35]. This description also applies to tasks often used to induce mental fatigue and certain commonalities can be observed between both constructs. However, studies on self-regulatory depletion tasks (often referred as "ego depletion") are more often encountered within the (exercise) psychology literature and usually use shorter tasks (≤30min), while within exercise physiology the term mental fatigue is more common and the fatiguing cognitive tasks are of longer duration (≥30min). Consequently, one should be careful and cautious in comparing the results in both lines of research.

1.2.2 Implications for daily life

Mental fatigue can have negative implications in daily life. It can ensue after only 60 min of driving and is associated with a difficulty in maintaining skilled driving behaviour [36]. In the workplace, mental fatigue has been found to be a major contributor to workplace accidents, morbidity, and mortality [37-39]. It has been found to predict an increased risk of error of surgeons [40], industrial workers [41], while during military operations it has been found to impair physical and cognitive ability [42]. Among the employees of the Flemish Government, 'general mental dysfunction', which includes mental fatigue, is the main cause of absenteeism at work in 2014 [43]. According to the Flemish Workability Monitor, 29.3% of the Flemish employees and 38% of the Flemish self-employed experience 'mental fatigue' in a problematic way. Problematic as in requiring a longer time than normal to recover from work-load or eventually resulting in an increase of risk for health-problems (e.g. burn-out). According to the Sociaal-Economische Raad van Vlaanderen (SERV)-report, people with acute mental fatigue problems can be assumed to have a higher risk for developing burn-out and hence, have a higher risk of being absent. Work-related circumstances associated with a higher risk for mental fatigue-related problems are for instance: higher work-load (odd-ratio (OR) = 6.34), lack of autonomy and variety in the work-task (OR = 1.89 and OR = 1.45, respectively), lack of support (OR = 2.73) and physically and emotional intensive work-circumstances (OR = 1.84 and OR = 2.68, respectively).

Consequently, insights in the mechanisms of mental fatigue via the line of research on the interaction between mental fatigue and physical performance might prove to be extremely valuable to gain further insight in the implications of mental fatigue in other aspects of daily life. These insights will in turn form the basis for translational research and for future studies exploring how to improve strategies to avoid/overcome mental fatigue.

1.3 PhD aims and format

In order to provide a clear oversight on physical performance in a mentally fatigued state a first aim in this PhD was to conduct a systematic review of the available literature on the topic (see Chapter 2). Although replication studies are still needed to confirm the observed tendencies in this systematic review, it was concluded that endurance and cognitive load appear to be two important components of physical performance that determine whether mental fatigue negatively impacts on performance or not. Thus, the shorter and more maximal the task, the lower the impact of mental fatigue on performance. This statement seems to be supported by the null findings in the studies on the effect of mental fatigue on maximal strength, power, and anaerobic work. In our search to further explore and substantiate these statements we subsequently aimed to assess in further detail the effect of ambient temperature on the mental fatigue-induced endurance impairment, the impact of mental fatigue on sport-specific psychomotor skills and possible countermeasures of mental fatigue.

These aims eventually resulted in the present PhD dissertation, consisting of one systematic review of the literature and four randomized controlled trials. All five manuscripts are written as stand-alone papers of which four have been accepted and one is submitted in relevant international exercise physiology, psychology and behavioural neuroscience journals. In this dissertation each manuscript is included as a separate chapter, except for chapter 3, in which two manuscripts will be handled together due to their shared main topic. Throughout this PhD the cited references were included as a separate list at the end of each chapter. To facilitate reading, abbreviations were defined at their first appearance within each chapter and the numbering of figures and tables was restarted in each chapter. As all the manuscripts included in this PhD are independent but linked, at times there is a necessary overlap between chapters.

- Mental fatigue and physical performance; literature review (Chapter 2)
    - **Research Question 1:** Does mental fatigue affect physical performance, and if yes, what are the underlying factors?
- Mental fatigue and the heat-induced decrease in endurance performance (Chapter 3)
    - **Research Question 2:** Does mental fatigue affect endurance performance in the heat?
    - **Research Question 3:** Does a heat pad, locally applied to the upper back, impair endurance performance?
- Mental fatigue and sport-specific psychomotor performance (Chapter 4)
    - **Research Question 4:** Does mental fatigue impair sport-specific psychomotor performance?
    - **Research Question 5:** Does level of training affect the impact of mental fatigue on sport-specific psychomotor performance?
- Counteracting mental fatigue (Chapter 5)
    - **Research Question 6:** Does serial caffeine-maltodextrin mouth rinsing counteract mental fatigue?

1.4 Mental fatigue and physical performance; Outline of the thesis

1.4.1 Mental fatigue and physical performance; literature review

The line of research on mental fatigue and physical performance originates from Angelo Mosso. In 1891, Angelo Mosso reported in his seminal book on fatigue that muscle endurance was reduced in two fellow professors of physiology after long lectures and verbal examinations [44]. More than a century later, Marcora et al. [25] investigated for the first time in an experimentally controlled way the effect of mental fatigue on physical performance and brought the existence of this effect of mental fatigue on physical performance, back to attention. The results of Marcora et al. [25] demonstrate that 90 min of a cognitively demanding task elicited mental fatigue and impaired subsequent cycling time to exhaustion (TTE). Furthermore, this study indicated that mental fatigue limits exercise tolerance in humans through higher perception of effort rather than cardiorespiratory and musculoenergetic mechanisms. A couple of years thereafter the negative effect of mental fatigue on endurance performance was confirmed by Pageaux et al. [45]. In this study it was shown that a submaximal isometric knee extensor exercise until exhaustion was impaired when mentally fatigued [45]. Again, the negative effect of mental fatigue on endurance performance seemed to be mediated by the higher perception of effort rather than impaired neuromuscular function [45]. Following up on these two studies the line of research on mental fatigue and physical performance was created and multiple other studies were conducted and published. In order to provide a clear oversight on physical performance in a mentally fatigued state a first aim in this PhD was to conduct a systematic review of the available literature on the topic.

<u>Research Question 1:</u> ***Does mental fatigue affect physical performance, and if yes, what are the underlying factors?***

1.4.2 Mental fatigue and the heat-induced decrease in endurance performance

1.4.2.1 Mental fatigue and cycling performance in the heat

Mental fatigue deteriorates cycling endurance performance [25, 27] in a normal ambient temperature (~20°C). Athletes have to be able to perform in a wide range of environmental conditions and one important factor within these conditions is ambient temperature. Heat stress, like mental fatigue, is also known to impair endurance performance [46]. As such from an applied point of view it is of importance to assess whether the mental fatigue- and the heat-induced performance decrements could work synergistically and deteriorate performance even further. Besides additional information from an applied point of view, assessing the effect of mental fatigue on endurance performance in the heat could also provide further mechanistic insights. The heat-associated impairment in performance has frequently been linked with a rise in cardiovascular strain [47] during endurance exercise, a decrease in maximal aerobic capacity, a higher internal body temperature (Tcore), a higher skin temperature (Tskin) [48], hypohydration [48], neuromuscular changes within the central nervous system [49], and an altered metabolic profile in the activity-dependent muscle groups [50]. Apart from all these physiological alterations during exercise in the heat, perceptual responses (thermal sensation, thermal discomfort, and perception of effort; i.e. subjective thermal strain) are also affected. Traditionally, the effects of heat on these perceptual responses have been explained as a consequence of the increased physiological strain [50]. However, we still do not know why perception of effort is higher during exercise in the heat. This could be due to the increased physiological strain, but direct effects of heat on the brain could also be the cause [51]. Similarly, we do not know why perception of effort during exercise is higher in mentally fatigued individuals [25]. However, we can exclude physiological strain [25] and neuromuscular fatigue [34] as there have been no differences observed in these parameters due to mental fatigue. Heat stress might augment the effect of mental fatigue on endurance performance by aggravating the mental fatigue induced by a given prolonged demanding cognitive task and/or by affecting perception of effort through a different and additive mechanism. Therefore, a second aim in this PhD was to assess the effects of mental fatigue on endurance performance in the heat (see Chapter 3).

<u>Research Question 2:</u> ***Does mental fatigue affect endurance performance in the heat?***

1.4.2.2 The role of perceptual responses in the heat-induced decrease in endurance performance

In this study we progress in our search for the role of perceptual responses in the heat-induced decrease in endurance performance. Because, as mentioned before, in addition to physiological strain, performing endurance exercise in the heat is associated with significant subjective thermal strain [52]. This strain is indicated by ratings of heat sensation, thermal discomfort and higher perceived exertion. It is generally accepted that subjective thermal strain plays a role in the deterioration of endurance performance observed in the heat [52-54]. Nonetheless, the exact extent to which it causes this deterioration is unknown as it is difficult to dissociate subjective thermal strain from the general physiological strain normally associated with impaired endurance performance in the heat (e.g. increased core temperature and decreased cardiac output).

Gaining further insight in the role of perceptual responses in endurance performance is of importance in this PhD as the impairment in endurance performance due to mental fatigue seems to be related to an increase in the perceived exertion, independently of the general physiological strain that is normally associated with exhaustion (e.g. increased core temperature, decreased cardiac output). To emphasize the important role of perceptual responses in endurance performance, Marcora introduced the psychobiological model of endurance performance based on the motivational intensity theory (see Fig. 1) [55-57]. This effort-based decision-making model postulates that an endurance performance is a motivated behaviour ultimately determined by two cognitive and motivational factors: perceived exertion and potential motivation, i.e., the maximum effort an individual is willing to exert to satisfy a motive [58]. Since mental fatigue was found not to affect potential motivation in the experiment of Marcora et al. [25] and others [30, 45, 59], the key to understand its negative effect on endurance performance is the higher perception of effort. Therefore, a third aim in this PhD was to gain understanding in the role of perceptual responses, independently from physiological strain, in endurance performance (see Chapter 3). In an attempt to do so, a heat pad was locally applied to the upper back during an endurance performance. This locally applied heat pad was expected to induce subjective thermal strain without affecting performance-determining physiology (e.g. core temperature, cardiac output), to subsequently be able to evaluate the independent role of subjective thermal strain in endurance performance.

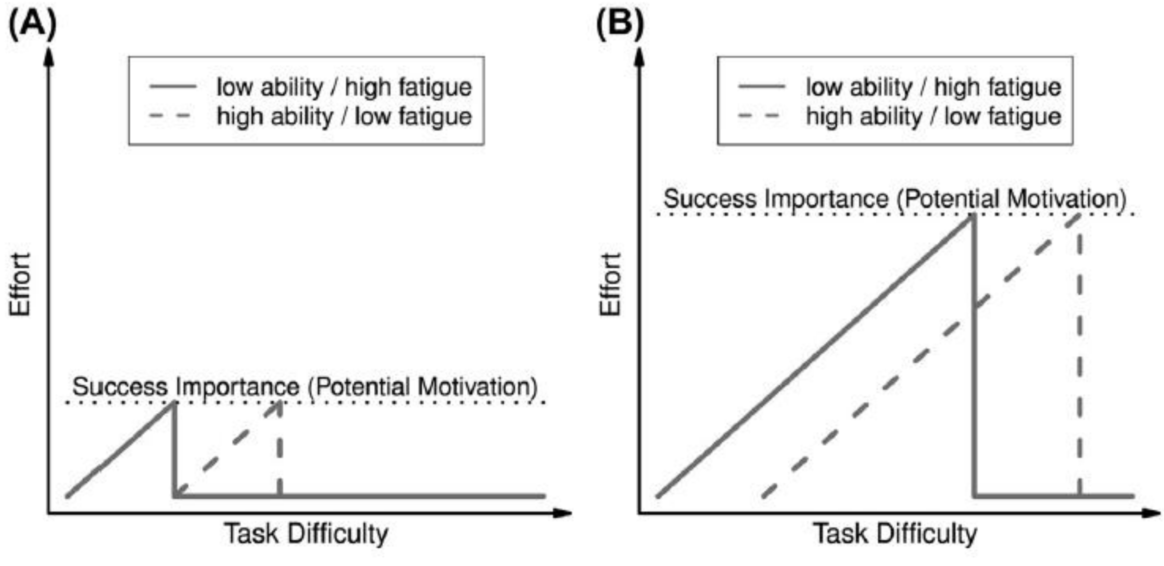

Fig 1. The motivational intensity theory [57]

<u>Research Question 3:</u> ***Does a heat pad, locally applied to the upper back, impair endurance performance?***

<u>1.4.3 Mental fatigue and sport-specific psychomotor performance</u>

It is clear that mental fatigue impairs physical performance and particularly endurance capacity [25, 27, 30]. Contrarily mental fatigue appears to have limited influence on maximal voluntary activation and strength, explosive power, and anaerobic work capacity [45, 60, 61]. Less or almost nothing is however known on the effect of mental fatigue on sport-specific psychomotor performance (e.g. visuomotor response time, tactical decisions,

…). Besides endurance capacity, this specific aspect of physical performance is a candidate proxy to be impaired by mental fatigue as a cognitive component has been put forward to be an important factor in observing an effect of mental fatigue on physical performance [60] and psychomotor skills rely heavily on optimal information processing/cognition [62]. Psychomotor skills require integrated control by the central and peripheral nervous systems. The decision to act is made by the higher centres of the brain, particularly the prefrontal cortex, and action is initiated by the premotor cortex and/or supplementary motor area, with the former being primarily concerned with movement in response to external events while the latter mainly controls voluntary movement, although both are active during any type of movement [62]. Sport-specific psychomotor skills encompasses anticipation on an opponents' behaviour, pattern recognition, strategic decision making, visual search behaviour, … , and is of crucial importance in every sport. Despite it is crucial in every sport it particularly defines performance in open-skill sports, i.e. sports in which players are required to react in a dynamically changing, unpredictable and externally-paced environment (e.g. basketball, fencing and badminton) [63]. Therefore, to enlarge our knowledge on the different aspects of physical performance that are impaired by mental fatigue, the goal in Chapter 4 was to assess whether sport-specific psychomotor performance related to open-skill sports (measured as visuomotor response time) are also impaired by mental fatigue.

Research Question 4: ***Does mental fatigue impair sport-specific psychomotor performance?***

In addition, the aspect of training could provide important insights in the trainability of resistance to mental fatigue, as such research question 5 was assessed in athletes as well as controls.

Research Question 5: ***Does level of training affect the impact of mental fatigue on sport-specific psychomotor performance?***

1.4.4 Counteracting mental fatigue

The finding that mental fatigue negatively affects physical performance triggers the urge to develop countermeasures that allow to avoid/overcome this kind of fatigue in an athletic setting. Mouth rinsing is a nutritional strategy that involves rinsing of substrates within the mouth for several seconds (5–20 s) without ingesting the solution, and thus avoids the possible negative side effects of intake of the substance. The rinsing of a solution containing carbohydrates, caffeine or both, has been shown to reduce fatigue and performance during exercise [64-66]. However, to the best of our knowledge, the use of mouth rinsing with both carbohydrates and caffeine as a mental fatigue countermeasure had never been tested before this PhD. Therefore, we sought to assess the effects of frequent mouth rinsing with a caffeine-maltodextrin (CAF-MALT) solution during a prolonged and demanding cognitive task (serial mouth rinsing) on various markers of mental fatigue.

Research Question 6: ***Does serial CAF-MALT mouth rinsing counteract mental fatigue?***

Neurophysiological measures played an important role in order to check whether mental fatigue was successfully counteracted by the CAF-MALT mouth rinse in this chapter. Multiple (neuro)physiological measures have been proposed to mirror the level of mental fatigue to some degree (e.g. electroencephalography (EEG), functional near infrared spectroscopy (fNIRS), heart rate (HR) variability, …) [23, 67, 68], one of the most promising is EEG.

When cortical neurons process information (cerebrocortical processing), the flow of the electrical currents across their membranes changes. These changing currents generate electrical fields that can be recorded with EEG, in this way providing a window on the dynamics of human brain functioning. Cortical oscillations can be divided into distinct bands [delta (δ), theta (θ), alpha (α), beta (β), and gamma (γ)], and the analysis of the cortical oscillations (frequency analysis) deals with transforming the time domain components to frequency domains (to obtain a power spectrum). The power in each frequency band reflects the number of neurons that discharge synchronously. An increase in power therefore means a mounting synchronization of neurons within that specific frequency band. On the contrary, a decrease in power reflects a desynchronization of neurons. Desynchronization seems to imply that different oscillators within a specific band are no longer coupled and start to oscillate with different frequencies. These different oscillators most likely reflect the synchronous activity of cortical or thalomocortical networks in a more local manner [69] and are, for example in the case of α-activity, termed local or functional alphas and facilitate cognitive processing [70]. a shift towards low-frequency bands (δ, θ, α) is frequently reported in mentally fatigued subjects [23, 67, 71-74], while higher frequencies (β, γ) typically decrease in amplitude [36]. This shift in spectral distribution is suggested to be related to a decrease in the level of arousal [75]. A study of Wascher et al. [23] reported mental fatigue is specifically associated with an increase in frontal θ and frontal and occipital α activity, which are associated with a reduced level of arousal and subsequent attention deficits [70, 76]. Besides the frequency domain of EEG, event-related potentials (ERP) have also been associated with the onset of mental fatigue. The event-related potentials' peak amplitude and –latency are, amongst other things, related to stimulus evaluation and recall of task rules [77] and subsequently also provide an important window to look into the brains functioning. The P300 is a component of an ERP that appears around 300 ms after the onset of a stimulus and its amplitude is suggested to serve as an electrophysiological marker of attentional resource allocation while its latency reflects the speed of stimulus evaluation [78, 79]. Käthner et al. [80] studied the influence of mental fatigue on P300 and observed a reduced P300 amplitude at the end of a mentally fatiguing task compared to at the beginning. Likewise Hopstaken et al. [28] also found a decrease in P300 amplitude with increasing subjective mental fatigue and time-on-task.

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Chapter 2: Mental fatigue and physical performance; literature review

The effects of mental fatigue on physical performance: a systematic review.

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2.1 Abstract

Background: Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity. Mental fatigue has recently been suggested to affect physical performance.

Objective: To evaluate the literature on the impairment in physical performance due to mental fatigue and to create an overview of the potential factors underlying this effect.

Data Sources: Two electronic databases, PubMed and Web of Science (until 28 April 2016) were searched.

Eligibility criteria for selecting studies: Studies had to be designed to test whether mental fatigue influenced performance on a physical task or influenced physiological and/or perceptual responses during the physical task. Studies using short (<30 min) self-regulatory depletion tasks were excluded from the review.

Results: Eleven articles were included, of which six were of strong and five of moderate quality. The general finding was a decline in endurance performance (decreased time-to-exhaustion and self-selected power output/velocity or increased completion-time) due to mental fatigue, associated with a higher than normal perceived exertion. Physiological variables traditionally associated with endurance performance (heart rate, blood lactate, oxygen uptake, cardiac output, VO_2) were unaffected by mental fatigue. Maximal strength, power and anaerobic work were observed not to be affected by mental fatigue.

Conclusion: Duration and intensity of the physical task appear to be important factors in the decrease in physical performance due to mental fatigue. The most important factor responsible for the negative impact of mental fatigue on endurance performance is a higher perceived exertion.

2.2 Keypoints

- Mental fatigue impairs endurance performance, while maximal strength, power and anaerobic work are not affected
- The impairment in endurance performance due to mental fatigue is mediated by a higher-than-normal perception of effort
- Future studies should use appropriate paradigms to induce mental fatigue and explore the role of the cognitive component and the intensity/duration of the endurance task in the effect of mental fatigue on endurance performance

2.3 Introduction

Mental fatigue represents a psychobiological state caused by prolonged periods of demanding cognitive activity [1, 2] and has implications on many aspects of daily life. In the workplace, mental fatigue has been found to predict an increased risk of error [3] and in addition it is one of the most common symptoms experienced by individuals with neurological disorders [4]. Mental fatigue can be manifested subjectively, behaviourally and physiologically. Subjectively, increased feelings of tiredness, lack of energy [5] and a decrease in motivation [6] and alertness have been reported [7]. Behaviourally, mental fatigue is recognized as a decline in performance (accuracy and/or reaction time (RT)) on a cognitive task [8-10]. Finally, alterations in brain activity [8, 11-13] have been shown to be a physiologic manifestation of mental fatigue. Changes in all three of these areas (subjective, behavioural, and physiological) do not have to be present for mental fatigue to be present. For instance, cognitive performance does not necessarily decline when one is mentally fatigued, since compensatory effort (e.g. indicated by alterations in brain activity or as a result of increased motivation) may alleviate this [9, 13]. Hopstaken et al. [13] increased motivation near the end of a prolonged cognitively demanding task by providing a monetary incentive and found that cognitive performance declines were reversed, despite previous signs of mental fatigue. This suggests, as previously stated, that the effects of mental fatigue can be counteracted by increased motivation and that one can be mentally fatigued without any cognitive impairment.

In 1891 Angelo Mosso reported in his seminal book on fatigue that muscle endurance was reduced in two fellow professors of physiology after long lectures and oral examinations [14]. More than a century later Marcora et al. [10] investigated for the first time in an experimentally controlled way the effect of mental fatigue on physical performance (whole-body endurance task). Muscular endurance tasks (e.g. sit-ups, weight holding, hand-grip tasks and leg-raise tasks) mostly involve a single muscle or muscle group [15]. In contrast, whole-body endurance performance refers to the entire body's ability to sustain prolonged (>75 s), dynamic exercise using large muscle groups (>2 legs; e.g. running, cycling and rowing) [16]. The results of Marcora et al. [10] demonstrate that 90 min of a cognitively demanding task elicited mental fatigue and negatively affected subsequent whole-body endurance performance. In addition the negative effect of mental fatigue on muscle endurance reported by Mosso [14] was recently confirmed in a study by Pageaux et al. [17]. In this study it was shown that a submaximal isometric knee extensor exercise until exhaustion was impaired when mentally fatigued.

Besides endurance, another important element of physical performance is high-intensity, anaerobically-based exercise (e.g. maximal strength, power and anaerobic capacity). This kind of performance is more likely to result in peripheral fatigue (i.e. fatigue produced by changes at or distal to the neuromuscular junction [18]) and therefore distinguishes itself from endurance performance. High-intensity, anaerobically-based exercise is often characterized by an all-out strategy (i.e. the athlete working maximally from the start of the event and rapidly fatiguing as a result [19]) and can be defined as any short-duration (<75 s) local muscle (e.g. maximal voluntary contraction (MVC)) or whole-body exercise (e.g. Wingate) that is powered primarily by metabolic pathways that do not use oxygen. This indicates that high-intensity, anaerobically-based performance will mostly require fewer decision-making processes (e.g. pacing) compared to endurance performance, due to the all-out strategy (i.e. less pace regulating) and due to the inherent shorter duration of these kind of performances.

The aim of the present paper is to review the literature on the effects of mental fatigue on physical performance and, if there are any, to create an overview of the potential underlying factors. In accordance with most of the included articles in the current review, the term ‘mental fatigue’ will be used [10, 12, 20, 21]. However some haziness exists in regard to its terminology. Some authors, like Ackerman & Kanfer [22] and MacMahon et al. [23], argued that the typical task used to induce mental fatigue is more appropriately termed cognitive. Therefore instead of ‘mental fatigue’ these authors used the term ‘cognitive fatigue’. It is our opinion that ‘mental fatigue’ is more appropriate as it includes emotion and motivation rather than just cognition. The term mental fatigue better encompasses constructs like cognition, sensation and perception and the complex interactions between these constructs. Bray et al. [24-26] and Pageaux et al. [20] labelled the mental fatigue inducing intervention as a ‘self-regulatory depletion manipulation’. Self-regulation refers to the mental abilities that allow people to exert control over their behaviours, thoughts, and emotions to pursue their goals [26, 27]. This description also applies to tasks often used to induce mental fatigue and certain commonalities can be observed between both constructs. As a consequence studies using self-regulatory depletion tasks that meet the eligibility criteria (duration 30 min or more) will also be included in the present review. However, studies using shorter self-regulatory depletion tasks (often referred as “ego depletion”) will not be included. It should also be stressed that this review will not include dual-task performance studies. The focus of the current review will be the influence of a preceding mentally fatiguing task on subsequent physical performance in order to adequately assess if and how performance is affected by mental fatigue.

2.4 Methods

2.4.1 Eligibility criteria

We used Population, Intervention, Comparison, Outcome and Study design (PICOS) criteria for papers in order to be included in this review (see Table 1; [28]). Randomized controlled trials (RCTs), non-randomized controlled trials (nRCTs) and non-randomized non-controlled trials (nRnCTs) were included. These studies had to be designed to test (observe in case of nRnCTs) whether a mentally fatiguing task (= intervention) influenced performance on a physical task or influenced physiological and/or perceptual responses during the physical task. To be able to test this, the control intervention (which will potentially also induce some degree of mental fatigue) in RCTs and nRCTs logically had to induce less or no mental fatigue compared to the mentally fatiguing task. Studies using short (<30 min) cognitive "self-regulation depletion" tasks were excluded from the review. This cut-off is an important feature of this review. A recent multi-laboratory replication study of the self-regulation depletion effect did not succeed in replicating the self-regulation depletion effect [29]. The authors state that although the self-regulation depleting task used may be sufficiently arduous, as indicated by difficulty, effort, and frustration ratings, it may not have been of sufficient duration or intensity to result in fatigue, a candidate proxy measure of depletion [29]. This emphasizes the importance of the length of the task used to elicit mental fatigue. The cut-off point was set at 30 min based on the vigilance decrement that typically occurs after 20–30 min of continuous work on the tasks used to induce mental fatigue [30]. In addition subjective increases in mental fatigue have been observed to occur in a similar time range (30 min; [31]). Only original studies written in English were considered.

Table 1 PICOS (Participants, Interventions, Comparisons, Outcomes, Study design)

PICOS component	Detail
Participants (P)	Humans, healthy
Interventions (I)	Inducing mental fatigue with a cognitive task of 30min or longer
Comparisons (C)	Non or less mentally fatigued individuals
Outcomes (O)	Physical performance, physiological and perceptual strain
Study designs (S)	RCTs, nRCTs and nRnCTs

Randomized Controlled Trial (RCT), non-Randomized Controlled Trial (nRCT), non-Randomized non-Controlled Trial (nRnCT)

2.4.2 Information Sources and Search Strategy

Two electronic databases, PubMed and Web of Science (until 28 April 2016) were searched. Medical Subject heading (MeSH) terms, if available in PubMed, were used to have a qualitative literature search. The following key-words were applied individually and combined: ‘mental fatigue (MeSH)’, ‘mental fatigue’, ‘mental exertion’, ‘cognitive fatigue’, ‘self-control strength depletion’, ‘ego depletion’ in combination with ‘athletic performance (MeSH)’, ‘physical performance’, ‘performance’, ‘muscle fatigue (MeSH)’, ‘central fatigue’, ‘peripheral fatigue’, ‘physical exercise’ (see Table 2). In addition, the reference lists of included articles were screened to make sure that important works were not omitted.

Table 2 Number of hits on keywords and combined key words in both search engines (PubMed & Web of Science)

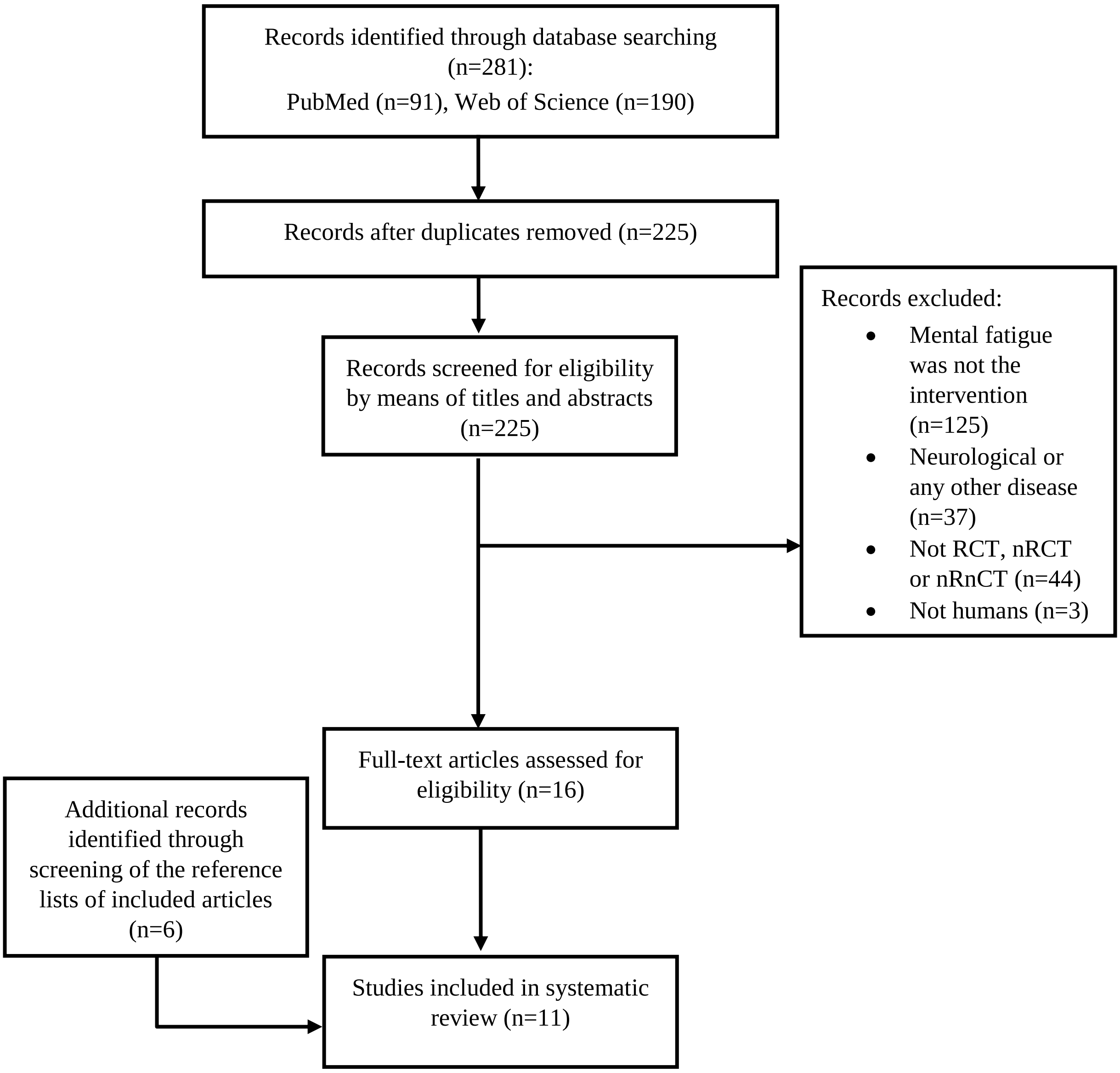
	PubMed		Web of Science	
Key words	**Hits (28/04/16)**	**Selected articles**	**Hits (28/04/16)**	**Selected articles**
(1) Mental fatigue (MeSH) OR mental fatigue OR mental exertion OR cognitive fatigue OR self-control strength depletion OR ego depletion	10 409	/	29 013	/
(2) Athletic performance (MeSH) OR physical performance OR performance	741 110	/	4 132 391	/
(3) Muscle fatigue (MeSH) OR central fatigue OR peripheral fatigue	13 036	/	68 089	/
(4) Physical exercise	317 864	/	401 479	/
Combined key words	**Hits (28/04/16)**	**Selected articles**	**Hits (28/04/16)**	**Selected articles**
(1) AND (2)	2 159	/	6 095	/
(1) AND (3)	978	/	5 235	/
(1) AND (4)	1 378	/	1 781	/
* (1) AND (2) AND (3) AND (4)	91	3	190	2

* Combined keywords were included in the screening process.

2.4.3 Study Selection and Data Collection Process

In- or exclusion of articles was performed by applying the PICOS-criteria (see Table 1) on the title, abstract and/or full text of articles. First, titles and abstracts of the articles were screened. Next, full-text articles were retrieved if the citation was considered potentially eligible and relevant. The data collection process is presented in Fig. 1 [32].

Fig. 1 PRISMA flowchart describing the process of obtaining the research articles (n=11) included in this systematic review [32]



2.4.4 Quality Assessment

The methodological quality was assessed using the quantitative assessment tool ‘QualSyst’ of Kmet et al. [33]. QualSyst contains 14 items (see Table 3) that were scored depending on the degree to which the specific criteria were met (“yes” = 2, “partial” = 1, “no” = 0). Items not applicable to a particular study design were marked “n/a” and were excluded from the calculation of the summary score. A summary score was calculated for each article by summing the total score obtained across relevant items and dividing it by the total possible score. Two reviewers (J.V.C. and B.R.) independently performed quality assessments, and disagreements were solved by consensus or by a third reviewer (K.D.P.). An article that scored ≥75% was considered strong, a score between 55% and 75% was considered moderate and a score ≤55% was considered weak.

2.5 Results

2.5.1 Study Selection

Our search resulted in 281 hits, of which 16 remained after excluding duplicates and screening of the titles and abstracts (Fig. 1). Eventually five articles were included, but screening of the reference lists of these five included articles resulted in the inclusion of six additional articles, making a total of 11 selected articles. Quality assessment of these 11 selected articles determined six articles were of strong quality and five articles were of moderate quality (see Table 3).

Table 3 Quality assessment 'Qualsyst' [33]

Study	A	B	C	D	E	F	G	H	I	J	K	L	M	N	**Rating**
Marcora et al. [10]	2	2	2	2	N/A	0	1	2	2	2	2	0	2	2	**Strong**
Pageaux et al. [17]	2	2	2	2	N/A	2	1	2	1	2	2	0	2	1	**Strong**
Brownsberger et al. [12]	2	2	2	2	N/A	0	1	2	1	2	2	0	2	1	**Moderate**
Pageaux et al. [35]	2	2	2	2	N/A	0	1	2	1	2	2	0	2	2	**Strong**
MacMahon et al. [23]	1	2	2	1	N/A	0	1	2	2	1	2	0	2	2	**Moderate**
Budini et al. [34]	2	1	1	1	N/A	N/A	N/A	2	1	1	1	0	2	1	**Moderate**
Martin et al. [37]	2	2	2	2	N/A	0	1	2	1	2	2	0	2	2	**Strong**
Smith et al. [21]	2	2	2	2	N/A	0	1	2	1	1	2	0	2	2	**Moderate**
Duncan et al. [36]	2	2	2	2	N/A	0	0	2	1	2	2	0	2	2	**Moderate**
Pageaux et al. [20]	2	2	2	2	N/A	0	1	2	1	2	2	2	2	2	**Strong**
Smith et al. [31]	2	2	2	2	N/A	2	1	2	1	2	2	0	2	2	**Strong**

A=Question described?, B=Appropriate study design?, C=Appropriate subject selection?, D=Characteristics described?, E=Random allocation?, F=Researchers blinded?, G=Subjects blinded?, H=Outcome measures well defined and robust to bias?, I=Sample size appropriate?, J=Analytic methods well described?, K=Estimate of variance reported?, L=controlled for confounding?, M=Results reported in detail?, N=Conclusion supported by results?

2 = yes, 1 = partial, 0 = no, N/A = Not Applicable

Strong = ≥75%, Moderate = 55% ≥ 75%, Weak = ≤55%

2.5.2 Mental fatigue inducing interventions

All but one included article could be classified as a crossover RCT, Budini et al. [34] was classified as a nRnCT. Mental fatigue was induced by a prolonged demanding cognitive task, but this task varied between studies. Pageaux et al. [20, 35] and Smith et al. [31] used a 30-min modified version of the Stroop colour-word task, in the study of Duncan et al. [36] participants had to complete concentration grids for 40 min, Budini et al. [34] employed a 100-min switch task paradigm, while the other six studies [10, 12, 17, 21, 23, 37] used a 90-min version of the AX-continuous performance test (AX-CPT). In the RCTs, the control task was always time matched with the intervention task and was chosen to differ from the intervention task in such a way that mental fatigue was only or at least significantly more induced by the intervention task. The majority, eight studies [10, 12, 17, 21, 23, 31, 36, 37], used a time-matched emotionally neutral documentary or reading magazine as a control task. Pageaux et al. [20, 35] used a less mentally fatiguing (congruent, non-response inhibition) Stroop task, as evidenced by the faster reaction time and the lower rated mental demand and effort. In order to motivate participants and increase engagement during the cognitive tasks, seven out of the eleven studies gave some sort of monetary reward for the best performance in terms of RT and accuracy. In the most recent studies however [20, 31, 36] no incentives were provided. Six [10, 12, 17, 21, 23, 31, 34] studies reported a greater subjective mental fatigue after the intervention compared to after the control task. In the studies of Marcora et al. [10], Pageaux et al. [17] and Smith et al. [21] this was assessed with the Brunel Mood Scale (BRUMS). Brownsberger et al. [12] and Smith et al. [31] used a visual analogue scale ranging from 'not at all' to 'completely exhausted' to assess perceived fatigue and MacMahon et al. [23] used the Current Mood State Scale (a short version of the profile of mood states (POMS)) to assess subjective fatigue. From the five studies that observed no difference in perceived fatigue due to the cognitive task, two did not assess subjective fatigue [34, 36], two [20, 35] assessed fatigue similarly to Marcora et al. [10] with the BRUMS, and one [37] assessed fatigue similarly to MacMahon et al. [23] with the POMS. Four out of the six studies [10, 12, 17, 21, 23, 31] that observed a greater subjective fatigue after the intervention compared to the control task also observed a higher mean heart rate (HR) during the intervention [10, 17, 21, 23]. In two studies [10, 21] the greater subjective fatigue was also associated with a decline of accuracy. An increase in reaction time over time was observed by Budini et al. [34]. In the study of Brownsberger et al. [12] the increase in mental fatigue was associated with an increase in β-band activity of the prefrontal lobe. Eventually all 11 studies observed some additional measure of increased mental effort, demand or frustration in the intervention task compared to the control task. An overview of the mental fatigue inducing interventions can be found in Table 4.

Table 4 Overview of mental fatigue inducing interventions: Task characteristics and outcome measures

Study	Sample	Intervention (I)	Control (C)	Duration	Monetary incentive	Methodological characteristics	Outcome	Remarks
Marcora et al. [10]	10 M 6 F	AX-CPT	Watching a documentary	90 min	£50 best performance on AX-CPT £50 best cycling performance	RCT, crossover	MF ↑ after I compared to C (assessed using BRUMS), associated with a decline in cognitive performance (less correct responses to AX trials) HR ↑ during I compared to C	
Pageaux et al. [17]	10 M	AX-CPT	Watching a documentary	90 min	Ticket for a professional sporting event	RCT, crossover	MF ↑ after I compared to C (assessed using BRUMS) HR ↑ during I compared to C	No decline over time in ACC or RT on AX-CPT
Brownsberger et al. [12]	8 M 4 F	AX-CPT	Watching a documentary	90 min	$100 for the most vigilant participant during AX-CPT	RCT, crossover	MF ↑ after I compared to C (assessed using VAS) Increased β-band activity of the prefrontal lobe in the middle and after I, compared to C (assessed using EEG)	
Budini et al. [34]	12 M	Switch task paradigm	-	100 min	-	nRnCT	RT ↑ in time	
Pageaux et al. [35]	8 M 4 F	100% incongruent modified Stroop colour-word task	100% congruent Stroop colour-word task	30 min	A £10 Amazon voucher for overall highest score on Stroop	RCT, crossover	MF = after I compared to C (assessed using BRUMS) Higher mental demand and effort in I compared to C (assessed using NASA-TLX) HR ↑ during I compared to C	Despite no overt mental fatigue, the I was perceived as more mentally demanding Modified Stroop = words presented in red ink react on the real meaning of the word, all other words react on the colour of the word
MacMahon et al. [23]	18 M 2 F	AX-CPT	Watching a documentary +	90 min	50€ for best performance on AX-CPT	RCT, crossover	MF ↑ after I compared to C (assessed using CMSS)	

			3min AX-CPT before and after				Lower positive mood after I compared to C (assessed using CMSS) HR ↑ during I compared to C	
Martin et al. [37]	7 M 5 F	AX-CPT	Watching a documentary	90 min	$50 for best five performances on AX-CPT	RCT, crossover	MF = after I compared to C (assessed using POMS) A greater cognitive effort during I compared to C (assessed using RSME)	
Smith et al. [21]	10 M	AX-CPT	Watching a documentary	90 min	$50 for the best performance on AX-CPT	RCT, crossover	MF ↑ after I compared to C (assessed using BRUMS) Increased incorrect responses on the AX-CPT in time (assessed using AX-CPT) HR ↑ during I compared to C	
Duncan et al. [36]	7 M 1 F	Completing concentration grids	Watching a documentary	40 min	-	RCT, crossover	-	
Pageaux et al. [20]	12 M	100% incongruent modified Stroop colour-word task	100% congruent Stroop colour-word task	30 min	-	RCT, crossover	MF = after I compared to C (assessed using BRUMS) Higher mental and temporal demand and effort in I compared to C (assessed using NASA-TLX) HR ↑ during I compared to C	Results suggest presence of mental fatigue after both CT
Smith et al. [31]	12 M	100% incongruent modified Stroop colour-word task	Reading magazines	30 min	-	RCT, crossover	MF ↑ after I compared to C (assessed using VAS)	

- Not applicable, *AX-CPT* AX-continuous performance test, *ACC* accuracy, *BRUMS* The Brunel Mood Scale, *C* control, *CMSS* Current Mood State Scale, *CT* cognitive task, *EEG* electroencephalography, *F* female, *HR* heart rate, *I* intervention, *M* male, *MF* mental fatigue or self-reported fatigue or fatigue or general fatigue or subjective fatigue, *NASA-TLX* National Aeronautics and Space Administration Task Load Index, *nRnCT* non-randomized non-controlled trial, *POMS* Profile Of Mood States, *RCT* randomized controlled trial, *RPE* rating of perceived exertion, *RSME* rating scale of mental effort, *RT* reaction time, *VAS* visual analogue scale (perceived level of fatigue)

2.5.3 Endurance

2.5.3.1 Whole-body endurance

Behavioural

Homogenous subject groups were recruited in each study, allowing for comparisons between studies. The participants were healthy, young (21 – 26 y) and moderately trained (maximal aerobic capacity (VO_2): 48 – 56 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$; performance level 2 according to De Pauw et al. [38]; see Table 5). However, the experimental protocols differed, and consequently also the outcome measures of performance (see Table 5). Marcora et al. [10] used a fixed resistance (80% of the peak power output) time-to-exhaustion cycling protocol and observed a mean decrease of 15% in time-to-exhaustion due to mental fatigue with no change in revolutions per minute (RPM). Pageaux et al. [35] and MacMahon et al. [23] on the other hand selected a distance-clamped, self-paced running protocol and both reported an increased completion time when participants were mentally fatigued. An average 5% and 2% increase due to mental fatigue was reported respectively on a 5-km [35] and a 3-km running distance [23]. Moreover, while Pageaux et al. [35] completed their study in a laboratory setting, MacMahon et al. [23] showed this negative effect of mental fatigue is also present in a more applied setting (indoor track). Smith et al. [21] used a time-clamped (45 min), self-paced running protocol to observe the effect of mental fatigue on distance covered. The protocol was designed with low- and high-intensity activities. They observed that mental fatigue decreased the overall (2%) distance and the distance covered at low-intensity (3%), but not at high intensity. Logically, running velocity was lower overall and at low-intensity. In a second study Smith et al. [31] studied the effect of mental fatigue on a Yo-Yo intermittent recovery test, level 1. This test required participants to complete 2x20m runs (up and back) at progressively increasing velocities until one failed twice to complete the 2x20 m within the time limit. Smith et al. [31] observed a decrease in the covered distance in this test (16.3%) when mentally fatigued. Martin et al. [37] used a time-clamped cycling protocol, a 3-min all-out test. Their protocol aimed to observe the effect of mental fatigue on peak and mean power output and critical power. They found no difference in any of these measures due to mental fatigue. Brownsberger et al. [12] studied the effect of mental fatigue on power output with a time- (10 min) and ratings of perceived exertion- (RPE) clamped protocol, meaning that participants had to complete two 10-min cycling bouts at self-selected intensities representative of fairly light effort (RPE 11) and hard effort (RPE 15). Both in the RPE 11- and RPE 15-trial participants chose lower self-selected power outputs in the mental fatigue condition (respectively 16% and 8% lower). In the study of Pageaux et al. [20] the only behavioural measure was RPM, as their cycling protocol was time (6 min) and resistance-clamped (80%), there was however no difference in RPM due to mental fatigue.

Physiological

HR and blood lactate ([Bla]) were measured in all whole-body endurance studies except the studies of Brownsberger et al. [12], Pageaux et al. [20] and Smith et al. [31] who did not measure [Bla] (see Table 5). Only the studies of Marcora et al. [10] and Brownsberger et al. [12] observed differences during exercise due to the intervention. Marcora et al. [10] reported a higher HR and [Bla] at exhaustion in the control condition. Brownsberger et al. [12] reported a higher mean HR (4.3%) in the control condition during the RPE 11-bout. Besides HR and [Bla] other physiological measures were taken that could possibly explain the decrease in endurance performance when mentally fatigued. Marcora et al. [10] showed that mental fatigue did not influence oxygen uptake, stroke volume, cardiac output and blood pressure during a subsequent whole-body endurance performance. Also brain activity (α and β-activity in the prefrontal and the parietal lobe [12]) was not differently altered during a whole-body endurance performance after a mentally fatiguing task. The time course (pre – post whole-body endurance performance) of blood glucose [21] and neuromuscular function [central (maximal voluntary activation level) and peripheral (twitch and doublet parameters and electromyography measures) parameters] of the knee extensors also did not differ due to mental fatigue [20]. Regarding electromyography (EMG) root mean square during the whole-body endurance task, also no effect of mental fatigue on the rectus femoris was found [20]. Conversely, mental fatigue was associated with increased EMG root mean square of the vastus lateralis during the whole-body endurance task [20]. In addition Smith et al. [21] reported a lower VO_2 (6%) during the exercise-protocol in the mental fatigue condition.

Psychological

The most frequently measured psychological outcomes during the whole-body endurance task were perception of effort, motivation and subjective workload related to the exercise protocol (see Table 5). Perception of effort or perceived exertion (i.e. how hard, heavy, and strenuous a physical task is [39, 40]) was always assessed through Borg's 15-point RPE scale [41], except for the study of Smith et al. [21] in which they used the CR100 RPE scale, and was found to be higher during exercise in a mentally fatigued state in the studies of Marcora et al. [10], Pageaux et al. [20, 35] and Smith et al. [21, 31]. Marcora et al. [10] used a scale developed and validated by Matthews et al. [42]. They did not find any difference in success or intrinsic motivation related to the upcoming physical tasks between conditions. The same conclusion was drawn in the studies of Pageaux et al. [20, 35] and Smith et al. [21], who used the same scale to assess motivation. In the study of Martin et al. [37] a different scale (Situational Motivation Scale [43]) was used to assess motivation, but again no difference was detected in identified regulation, external regulation and amotivation. There was however a trend for a decrease in intrinsic motivation when mentally fatigued. Brownsberger et al. [12], MacMahon et al. [23] and Smith et al. [31] did not differentiate between different types of motivation. Brownsberger et al. [12] and Smith et al. [31] used a 10-cm visual analogue scale to assess motivation for the upcoming physical task, while MacMahon et al. [23] used a 7-point Likert scale. No effects of mental fatigue on motivation could be distinguished. The subjective workload of the exercise protocol was only assessed in the studies of Pageaux et al. [20, 35]. In Pageaux et al's 2014 article [35], the National Aeronautics and Space Administration Task Load Index found that the exercise protocol was perceived as more mentally demanding and participants also rated their performance on the time trial lower in the intervention trial. Additional psychological constructs like attentional focus [23] and mood after the exercise protocol [12] were also assessed, but no differences were observed due to mental fatigue.

Table 5 Overview of the effects of mental fatigue on endurance performance: Subjective, behavioural and physiological measures before, during and/or after the physical task

Study	Sample	Characteristics	MF ↑ compared to C	Motivation to exercise	Physical task	Time of physical task	Outcome	Remarks
Whole-body endurance								
Marcora et al. [10]	10 M 6 F	Trained, healthy A = 26 ± 3 y Mass = 69 ± 10 kg Wmax = 288 ± 70 W VO_2max = 52 ± 8 ml/kg/min	Yes	No difference in intrinsic and success motivation between conditions (assessed using scale by Matthews et al. [42])	Cycling time to exhaustion at 80% of Wmax	Post CT	Time-to-exhaustion ↓ in I compared to C RPE ↑ during exercise in I compared to C HR and [Bla] ↑ at exhaustion in C compared to I	Time-to-exhaustion in C = 754 ± 339 s
Brownsberger et al. [12]	8 M 4 F	Trained, healthy A = 24 ± 5 y Mass = 71 ± 15 kg VO_2max = 56 ± 6 ml/kg/min	Yes	No difference in motivation between conditions (assessed using VAS)	2 consecutive self-paced 10 min bouts of cycling exercise. One representative for RPE 11 (fairly light) and one for RPE 15 (hard)	Post CT	Self-selected power outputs ↓ in I compared to C for both RPE 11 and RPE 15 exercise bouts HR ↑ in C compared to I for the RPE 11 bout (4.3%) β-band activity ↑ during warm-up in I compared to C	
Pageaux et al. [35]	8 M 4 F	Trained, healthy A = 21 ± 1 y Mass = 69 ± 11 kg Aerobic activities 2x/week in the previous 6 months	No (more mentally exerted after I compared to C)	No difference in intrinsic and success motivation between conditions (assessed using motivation scale by Matthews et al. [42])	Run 5 km in the quickest time possible	Post CT	Performance ↓ in I compared to C No difference in pacing strategy between conditions RPE ↑ during exercise in I compared to C TT-performance was perceived lower and more mentally demanding in I compared to C	TT performed on a treadmill in a lab setting

MacMahon et al. [23]	18 M 2 F	Trained (familiarized with a 3 km run) A = 25 ± 3 y Running on average 2.84 ± 1.79 hr/week	Yes	No difference in motivation between conditions (assessed using a 7 point Likert scale) Greater decrease in positive mood when mentally fatigued compared to control (assessed using CMSS)	Run 3 km in the quickest time possible	Post CT	Performance ↓ in I compared to C RPE = during exercise in I compared to C No difference in attentional focus before and during exercise between conditions	TT performed on an indoor track Focus of attention was assessed using a 10 point bipolar scale
Smith et al. [21]	10 M	Healthy, competitive intermittent team sporters (for a minimum of 3 y) A = 22 ± 2 y Mass = 75 ± 6 kg VO_2max = 48 ± 6 ml/kg/min	Yes	No difference in intrinsic and success motivation between conditions (assessed using motivation scale by Matthews et al. [42])	45 min self-paced intermittent high-intensity running protocol, with LIA and HIA	Post CT	Overall and LIA velocity ↓ and total and LIA distance ↓ in I compared to C HIA and peak velocity = and HIA distance = between conditions Work performed at any intensity did not differ between conditions RPE = between conditions during running protocol RPE ↑ 30 min after running protocol	Running protocol was based on time motion analysis data from multiple team sports, six activities were included: LIA (stand, walk, jog and run) HIA (fast run and sprint)
Martin et al. [37]	7 M 5 F	Trained, healthy A = 23 ± 3 y VO_2max = 53 ± 13 ml/kg/min	No	Intrinsic motivation tended to be reduced postCT in MF-condition compared to C (assessed using SIMS)	3MT	Pre and post CT 3MT, only post CT	No difference in anaerobic work capacity or power (3MT) between conditions No difference in CMJ (explosive power) or MVC between conditions RPE tended to ↑ during 3MT in I compared to C	
Pageaux et al. [20]	12 M	Healthy active A = 25 ± 4 y	No	Motivation was not assessed	6 min cycling at 80% of Wmax	Cycling task post CT	No difference in MVC between both conditions	

		Mass = 77 ± 11 kg Moderate/high intensity exercise 2x/week in the previous 6 months				MVC pre and post CT and post cycling task	RPE ↑ during cycling in I compared to C No effect of mental fatigue on central or peripheral fatigue	
Smith et al. [31]	12 M	Moderately-trained soccer players	Yes	No difference in motivation between conditions (assessed using VAS)	Yo-Yo IR1	Post CT	Distance covered ↓ in I compared to C RPE ↑ during exercise in I compared to C No difference in HR between conditions	Distance covered in C = 1410 ± 354 m
Muscle endurance								
Pageaux et al. [17]	10 M	Active A = 22 ± 2 y Mass = 70 ± 8 kg	Yes	No difference in intrinsic and success motivation (assessed using scale by Matthews et al. [42])	To maintain 20% MVC of the knee extensor muscles until exhaustion	Post CT	Time-to-exhaustion ↓ in I compared to C Leg RPE ↑ during the exhaustion-task in I compared to C No difference in EMG activity between conditions	Time-to-exhaustion in C = 266 ± 26 s

3MT 3min all-out cycling test, *A* age, *BRUMS* The Brunel Mood Scale, *[Bla]* blood lactate, *C* control, *CMSS* Current Mood State Scale, *CT* cognitive task, *EMG* electromyography, *F* female, *HIA* high-intensity activity, *HR* heart rate, *I* intervention, *kg* kilogram, *km* kilometres, *LIA* low-intensity activity, *M* male, *m* meter, *MF* mental fatigue, *min* minutes, *ml* millimetre, *MVC* maximal voluntary contraction, *RPE* ratings of perceived exertion, *s* seconds, *SIMS* Situational Intrinsic Motivation Scale, *TT* time trial, *VAS* Visual Analog Scale, *VO_2max* maximal aerobic capacity, *W* watt, *Wmax* maximal wattage, *Y* years, *Yo-Yo IR1* Yo-Yo intermittent recovery test, level 1

2.5.3.2 Muscle endurance

Behavioural

Only one study evaluating the effect of mental fatigue on muscle endurance could be included in the present review [17] (see Table 5). In this study participants had to produce a target value of 20%-MVC (a prolonged submaximal isometric contraction of the knee extensor muscles) until exhaustion. Time-to-exhaustion was observed to be 13% shorter in the mental fatigue condition [17].

Physiological

HR was continuously monitored during this prolonged submaximal contraction and was not observed to be affected by mental fatigue at iso-time (time elapsed from the beginning of the endurance task to the last measurement before exhaustion of the shortest performance) nor at exhaustion. Likewise EMG root mean square did not differ between conditions [17].

Psychological

Leg-RPE (i.e. subjects were specifically asked to rate how hard they were driving their leg during the endurance task) was measured every 20 s and was significantly higher when mentally fatigued. At exhaustion leg-RPE did not differ [17]. No difference in intrinsic and success motivation towards the endurance task was observed during this investigation [17].

2.5.4 Maximal strength, Power and Anaerobic Work

Behavioural

Five studies examined the effect of mental fatigue on high-intensity, anaerobically-based exercise [17, 20, 34, 36, 37] (see Table 6). Four studies assessed whether an impairment in MVC of the knee extensor muscles occurred after completing a mentally fatiguing task [17, 20, 34, 37]. Both studies of Pageaux et al. [17, 20] revealed that the mentally fatiguing as well as the control task did not affect MVC torque. Martin et al. [37] confirmed these results and found no condition or time effect in any of the measures taken during the MVC (i.e. peak torque, mean torque, time to half peak torque, time to peak torque and peak torque slope). Budini et al. [34] on the contrary reported a decreased leg extension MVC (796 ± 150 N to 741 ± 137 N) after a 100-min mentally fatiguing task. Martin et al. [37] and Duncan et al. [36] examined the influence of mental fatigue on more sport specific anaerobic performance. Regarding a countermovement jump Martin et al. [37] found no difference in jump height, mean power, peak force, concentric peak velocity or eccentric displacement due to mental fatigue. Duncan et al. [36] reported that mental fatigue had no effect on mean cycling power during four consecutive 30-s Wingate anaerobic tests.

Physiological

Martin et al. [37] did not record any specific physiological measures related to the countermovement jumps. On the other hand Duncan et al. [36] assessed HR and [Bla] and found no difference due to mental fatigue. In the studies of Pageaux et al. [17, 20] and Budini et al. [34] measures of peripheral and central fatigue were examined during a MVC. Pageaux et al. [17, 20] included single electrical stimulation in order to evaluate peak twitch, time to peak twitch and half-relaxation time. Double electrical stimulation was used to evaluate the peak torque of the doublet (potentiated doublet, 5 s after the MVC). In both studies [17, 20] no effects of mental fatigue on peripheral parameters of neuromuscular function (peak twitch, time to peak twitch and half-relaxation time) or on central parameters (voluntary activation level) were observed [17, 20]. Budini et al. [34] made use of two springs with a different stiffness to induce two specific tremors during a 20-s 30%-MVC. One spring induced a 9-Hz frequency oscillation (associated with the peripheral component of the stretch reflex) and another a 5-Hz (associated with the central component of the stretch reflex). The instability/tremor at 9 Hz, generated by the stretch reflex peripheral component, was decreased after the mental fatigue task [34].

Psychological

Budini et al. [34] did not take any psychological measures and the measures (i.e. perception of effort, motivation and subjective workload) taken in the studies of Pageaux et al. [17, 20] were not related to the anaerobic maximal work. Duncan et al. [36] also employed few psychological measures, with only RPE being measured on completion of each Wingate-test, but no effect of mental fatigue was reported. Martin et al. [37] assessed RPE and motivation and did not observe any difference in RPE, identified regulation, external regulation and amotivation towards the countermovement jump or MVCs.

Table 6 Overview of the effects of mental fatigue on maximal strength - power - anaerobic work: Subjective, behavioural and physiological measures before, during and/or after the physical task

Study	Sample	Characteristics	MF ↑ compared to C?	Motivation to exercise	Physical task	Time of physical task	Outcome	Remarks
Pageaux et al. [17]	10 M	Active A = 22 ± 2 y Mass = 70 ± 8 kg	Yes	Motivation was not assessed	MVC (duration of ~5 s) with superimposed supramaximal paired stimuli (doublet) at 100 Hz and followed (4 s intervals) by paired stimuli at 100 Hz, (ii) 60 s rest and (iii) three single supramaximal stimulations at rest (interspaced by 3 s).	Pre and post CT and post cycling task	MF no effect on MVC MF no effect on neuromuscular function	
Budini et al. [34]	12 M	Healthy A = 29 ± 4 y	-	Motivation was not assessed	Two submaximal 20 s contractions of the knee extensor muscles at 30% MVC using a long and short spring Three 3 s MVCs of the knee extensor muscles	Pre and post CT	MVC ↓ when mentally fatigued (-6.9%) EMG activity ↓ within the 8-12 Hz frequency band when mentally fatigued	Short spring induces 8-12 Hz = stretch reflex peripheral component Long spring induces 3-6 Hz = stretch reflex central component
Martin et al. [37]	7 M 5 F	Trained, healthy A = 23 ± 3 y VO_2max = 53 ± 13 ml/kg/min	No	Intrinsic motivation tended to be reduced postCT in MF-condition compared to C (assessed using SIMS)	Three CMJ Three MVCs of the knee extensor muscles	Pre and post CT	No difference in CMJ (explosive power) or MVC between conditions	
Duncan et al. [36]	7 M 1 F	Trained, healthy (University level, team games)	?	Motivation was not assessed	Four 30 s Wingates (separated by 4 min rest)	Post CT	No difference in mean cycling power between conditions	No manipulation checks included

							No difference in RPE between conditions No difference in HR or [Bla] between conditions
Pageaux et al. [20]	12 M	Healthy active A = 25 ± 4 y Mass = 77 ± 11 kg	No	Motivation was not assessed	MVC (duration of ~4 s) with superimposed supramaximal paired stimuli (doublet) at 100 Hz and followed (4 s intervals) by paired stimuli at 100 Hz, (ii) 60 s rest and (iii) three single supramaximal stimulations at rest (interspaced by 3 s).	Pre and post CT and post cycling task	No difference in MVC between both conditions RPE ↑ during cycling in I compared to C No effect of mental fatigue on central or peripheral fatigue

- not applicable, *A* age, *[Bla]* Blood lactate, C control, *CMJ* countermovement jump, *CT* cognitive task, *F* female, *EMG* Electromyography, *min* minutes, *HR* heart rate, *Hz* hertz, *I* intervention, *kg* kilogram, *M* male, *MF* mental fatigue or self-reported fatigue or fatigue or general fatigue or subjective fatigue, *MVC* maximal voluntary contraction, *PT* physical task, *RPE* rating of perceived exertion, *s* seconds, *SIMS* Situational Intrinsic Motivation Scale, *Y* years

2.6 Discussion

With the present review we sought to outline the current knowledge on the effect of mental fatigue on physical performance. Secondly, we aimed to propose possible factors mediating this effect. All investigations included in this review were of moderate to strong quality (assessed with the quantitative assessment tool 'QualSyst' of Kmet et al. [33]). Within the quality criteria check all studies lost points for not blinding investigators and subjects. This highlights a specific difficulty in this field of research, being the impossibility to blind a participant from which task is being done, the experimental task (the cognitive task) or the control task (a less demanding cognitive task or watching a television documentary). This could lead to different expectations regarding the performance on a subsequent physical exercise task. This is predominantly counteracted by selecting so-called 'naïve participants', meaning they were naïve to the real aims and hypotheses of the study. Instead participants were told the study examined the effects of two different cognitive activities (a computerized task and watching television) on the physiological responses to exhaustive exercise [10] or were led to believe the study was examining whether watching television or completing a mentally engaging task is a good preparation for maximal anaerobic exercise performance [37]. Despite participants being deceived, the difference in task demand between the experimental and the control task could still have created different expectations concerning the subsequent physical performance. A solution might be to measure how participants expect to perform on the physical task, however this carries the risk of emphasizing a potential difference in performance-expectations between conditions.

2.6.1 Mental fatigue inducing interventions

One of the most important questions in studying the effect of mental fatigue on physical performance is whether mental fatigue was successfully induced. To answer this question a definition of mental fatigue and its markers is needed. As already stated in section 1, mental fatigue has subjective, behavioural and physiological manifestations. Most of the included studies assessed only the subjective and behavioural manifestations and therefore the quantification of mental fatigue is often restricted. Marcora et al. [10] postulated that higher subjective fatigue and/or a decline in cognitive performance indicate the presence of mental fatigue. However, whether the presence of these two markers is sufficient to determine that mental fatigue has been successfully induced is debatable. This is shown by the fact that only six of the 11 included studies observed higher subjective fatigue [10, 12, 17, 21, 23, 31] and only two studies reported a decrease in accuracy with longer time-on-task [10, 21]. Moreover, observing an increase in subjective fatigue or not, also greatly depends on the subjective scale that is used. A visual analogue scale assessing how mentally fatigued an individual feels might be sensitive but promote response bias, while the BRUMS or POMS may be less capable of detecting small but relevant short-term changes in mental fatigue. This raises the need for well-thought paradigms that account for the relative contribution of other parameters, like motivation and/or boredom, when time-on-task effects are investigated [9, 44]. In an attempt to account for these effects (e.g. loss of motivation with subsequent task disengagement), incentives were provided for the best performances in seven of the eleven included studies. Gergelyfi et al. [44] demonstrated that alterations of the motivational state through monetary incentives failed to compensate the effects of mental fatigue and therefore this seems a legitimate way to account for task disengagement (i.e. decrease in cognitive performance) through loss of motivation. Nonetheless, the interpretation of subjective and behavioural measures of mental fatigue remains challenging without (neuro)physiological measures.

Brownsberger et al. [12] is the only included study that used electroencephalography (EEG) to examine neural indices (α and β waves) of electrocortical activity in the prefrontal cortex, a brain region that is important in decision-making [5]. They reported an increased β-band activity of the prefrontal lobe in the middle of and after the mentally demanding task compared to the control task. β-waves are fast (13–30 Hz) EEG potentials associated with increased alertness, arousal and excitement [45]. Brownsberger et al. [12] subsequently interpreted this finding as an indication of successfully eliciting greater attention, information processing and cognitive engagement. This greater attention could of course indicate that compensatory mechanisms were in place to maintain performance in the presence of mental fatigue [46], however it does not automatically indicate that mental fatigue was present. The greater elicited attention and cognitive engagement rather suggests that the experimental task was more mentally demanding. EEG measures that have repeatedly been associated with the occurrence of mental fatigue are increases in frontal θ and in frontal, central and parietal α-power [8, 47-49]. Moreover, if one considers the continuous change of a measure as a criterion in order to assign it to the development of mental fatigue, the increase in frontal θ power seems to be the most valid measure of mental fatigue according to the data reported by Wascher et al. [8] and Trejo et al. [49]. Elevated θ activity shows that more effort is required to maintain the performance level, certainly when tasks have to be repeated [50-52]. Unfortunately θ activity was not measured in the study of Brownsberger et al. [12].

In order to state whether mental fatigue was induced requires subjective, behavioural and physiological measures, and the interactions between all three manifestation areas of mental fatigue should be interpreted. Moreover, adaptation, motivation and inter-individual differences in threshold to mental fatigue are important variables to account for. Participants have to be in a well-familiarized setting [9] in which subjective, behavioural and physiological effects can be most certainly attributed to mental fatigue. This could be attained by adding a different cognitive task before and after the mentally fatiguing task (i.e. the indirect method [53]), allowing researchers to evaluate the effect of fatigue on cognitive performance independently from time-on-task [44]. In addition it is likely that the occurrence of mental fatigue differs from one individual to another, and depends on the duration and/or difficulty of the mentally exerting task. Therefore, it cannot be expected that the same physiological, psychological and behavioural changes will be observed in all individuals. The importance of the duration of the task to induce mental fatigue is underlined by the recent replication study of Hagger et al. [29] and is shown again by a recent study published by Schücker et al. [54]. In this study [54] no effect of a 10-min cognitive task on subsequent whole-body endurance performance was found. The authors admit one possible explanation for these results is the ineffectiveness of the manipulation task (10-min Stroop) to induce mental fatigue. They however argue that even shorter tasks have been observed to reduce whole-body endurance performance [55] and therefore feel confident that the induced state of mental fatigue was comparable with previous studies in this line of research. However there seem to be some crucial differences between the lines of research on mental fatigue and self-regulation depletion [56]. More specifically, in the short tasks used in the self-regulation depletion research mental exertion is not sufficiently prolonged to induce subjective feelings of mental fatigue. Therefore one should be cautious about attributing the results in both lines of research to the same mechanism. In the end, all included studies in the present review but the studies of Pageaux et al. [20, 35], Martin et al. [37] and Duncan et al. [36] have arguments to state mental fatigue was induced in the experimental condition and not or to a lesser extent in the control condition. Despite not being able to substantiate mental fatigue was induced in their study, the studies of Pageaux et al. [20, 35], Martin et al. [37] and Duncan et al. [36] were included. To begin with, these studies

[20, 35-37] used tasks of a similar nature and length as the tasks used in the other included studies that were successful in inducing mental fatigue. Secondly, Duncan et al. [36] did not include any subjective, behavioural or physiological measures to monitor mental fatigue, whereas Pageaux et al. [20, 35] and Martin et al. [37] used the, perhaps too insensitive, BRUMS or POMS to assess the participants' state of mental fatigue. Therefore, and because in the studies of Pageaux et al. [20, 35] and Martin et al. [37] it was reported that participants perceived the intervention task as more mentally demanding and effortful compared to the control task, these studies were also included.

2.6.2 Mental fatigue and physical performance

For the purpose of discussing the subsequent physical performance in a mentally fatigued state a distinction was made between behavioural, physiological and psychological outcomes during exercise.

2.6.2.1 Behavioural

Out of the nine studies that examined the effect of mental fatigue on behavioural measures, eight included an endurance performance-measure. Seven of those eight reported that endurance performance was negatively affected by mental fatigue. This was evidenced by a decrease in time-to-exhaustion [10, 17], an increase in completion time [23, 35], a decrease in self-paced velocity [21], a decrease in self-selected power outputs [12] and a decrease in distance covered [31]. Only in the 3-min all-out protocol of Martin et al. [37] no impact of mental fatigue was observed. Martin et al. [37] argued that the lack of effect of mental fatigue on performance was caused by the reduced to non-existent cognitive component of the exercise task. Indeed, an all-out strategy is characterized by the athlete working maximally from the start of the event and rapidly fatiguing as a result of that [19]. This statement seems to be supported by the null findings in the studies on the effect of mental fatigue on maximal strength, power and anaerobic work [17, 20, 36, 37]. The employed physical tasks in these studies all require a maximal all-out effort. From these results it can be pointed out that it appears to be important to differentiate between endurance and maximal power tasks to observe a negative effect of mental fatigue on behavioural measures. This leads to the assumption that, the shorter and more maximal the task, the lower the impact of the mental fatigue. The distinction between whole-body and local muscle endurance tasks does not seem to be of great importance to find an effect of mental fatigue. In a study of Pageaux et al. [17] it was shown that besides whole-body endurance, muscle endurance was also impaired when mentally fatigued. This is however the only study examining the effect of mental fatigue on muscle endurance performance and needs to be confirmed by other studies in the future. The importance of both the cognitive component and the submaximal, endurance intensity in the physical task also points towards the need for future research to be conducted in a more applied way (e.g. in prolonged endurance tasks/events). The demands of such real life prolonged endurance events are physically but also cognitively high, as is shown by the metacognitive framework of Brick et al. [57]. Therefore such real life endurance events are possibly able to accentuate even more the decrease in endurance performance due to mental fatigue. A recent investigation by Brick et al. [58] demonstrated this by comparing an RPE-clamped time trial and an externally-controlled pace time trial. Preceding the randomized completion of these two time trials participants completed two self-controlled pace time trials. Pacing strategy for the externally-controlled and RPE-clamped time trials was the same as for the subjects' fastest self-controlled pace time trial. It was concluded that external control over pacing (e.g. drafting in a race) may facilitate performance [58], possibly mediated through reducing the cognitive load and promoting appropriate attentional strategies that optimize performance. An applied study was recently performed in soccer. Badin et al. [59] assessed the effect of mental fatigue on physical and technical performance in small-sided soccer games. Physical performance (total distance covered tracked with a global positioning system) in this setting was however not a main objective, because a player could perform better (e.g. more successful passes) without covering more distance. Therefore, because covering as much distance as possible did not translate unequivocally to a better performance in a small-sided soccer game and because the researchers also did not instruct the participants to cover as much distance as possible during the game, there was no real physical performance measure included in this study and consequently the study was not included in the review. Nonetheless studies of this kind are extremely useful and necessary in order to expand our knowledge on the effect of mental fatigue on physical performance.

2.6.2.2 Physiological

Regarding the studies on endurance performance, Marcora et al. [10], Brownsberger et al. [12] and Smith et al. [21] observed respectively a higher HR and [Bla] at exhaustion, a higher mean HR in the RPE 11 exercise-bout and a higher VO_2 in the control trial compared to the mental fatigue trial. However all these findings can be explained by behavioural changes. In the study of Marcora et al. [10] the longer time-to-exhaustion explained the physiological differences between conditions. Brownsberger et al. [12] identified the higher self-selected power-outputs as an explanation for the higher mean HR and Smith et al. [21] emphasized the higher self-selected running velocities to account for the higher VO_2 in the control trial. Brownsberger et al. [12] also observed elevated β activity in the prefrontal brain lobe during a 3-min warm-up due to mental fatigue. This significant difference disappeared during the subsequent exercise bout. Pageaux et al. [20] demonstrated that mental fatigue was associated with a higher EMG root mean square of the vastus lateralis during cycling. This suggests an alteration in muscle fibre recruitment for the same power output and was previously reported by a self-regulation study [24]. In contrast to the above mentioned physiological differences between conditions, it was also observed that many physiological measures did not differ. Marcora et al. [10] did not observe any effect of mental fatigue on cardiovascular measures during exercise. Pageaux et al. [20] used a time- and intensity fixed protocol in order to observe the effect of mental fatigue on exercise induced peripheral (twitch and doublet parameters and EMG measures) and central (voluntary activation level) fatigue. It could be concluded that mental fatigue did not accentuate peripheral fatigue as well as it did not increase exercise-induced central fatigue [20]. Overall, all included studies were rather unequivocal, mental fatigue does not reduce endurance performance by altering physiological, cardiorespiratory and neuromuscular responses to the subsequent exercise. These findings are confirmed by the line of research on the effect of mental fatigue on maximal strength, power and anaerobic work. Studies by Pageaux et al. [17], Martin et al. [37] and Rozand et al. [60] did not observe any effect of mental fatigue on central fatigue. In contrast, Budini et al. [34] reported a decreased MVC and a decreased tremor amplitude during a 100% MVC after a mentally fatiguing task (100 min). Weakened cortico-muscular coupling (i.e. synchronized activity of the motor cortex and the spinal motoneuron pool) induced by mental fatigue is one possible explanation for this finding [34]. Yet they did not include a control group and as a consequence muscle relaxation cannot be excluded as another potential explanation for their findings. These results demonstrate that mental fatigue is able to alter endurance performance without altering any exercise-induced physiological parameter in the periphery and without any change in the cortico-muscular coupling. A side note to this conclusion has to be that, due to the findings of Pageaux et al. [20] and Budini et al. [34], further investigations on the effect of mental fatigue on muscle fibre recruitment are warranted.

2.6.2.3 Psychological

Martin et al. [37] reported a trend for a decrease in intrinsic motivation towards the upcoming physical task when mentally fatigued. Moreover, Pageaux et al. [35] found that a 5-km time trial was perceived as more mentally demanding and participants also rated their performance on the time trial lower when mentally fatigued. The most consistent finding was however the higher RPE during exercise. Marcora et al. [10], Pageaux et al. [17, 20, 35] and Smith et al. [21, 31] all observed a higher RPE during exercise, Martin et al. [37] observed a trend towards a higher RPE and Brownsberger et al. [12] and MacMahon et al. [23] both showed a lower self-selected power output or running velocity for the same RPE. Therefore the current general opinion is that endurance performance is impaired by mental fatigue and this is predominantly related to the higher-than-normal perceived exertion during exercise. Mental fatigue appears not to alter motivation towards the upcoming endurance task. In the study of Marcora et al. [10] this could have been due to a ceiling effect, created by the artificially increased motivation by offering monetary reward for best cycling performance, that masked the possible influence of mental fatigue on motivation. However, no other studies provided monetary incentives to increase engagement in the physical task and a ceiling effect was therefore less plausible in those studies. Encouragements and visual feedback during the physical task itself are other important factors that impact on motivation. These specific aspects differed between studies, with some [20, 21] giving no feedback nor encouragement, some giving feedback but no encouragements [12, 31, 34, 35] and others giving both feedback and standardized encouragements [10, 17, 37]. However, independently from giving feedback or encouragements, all studies reported no effect of mental fatigue on motivation towards the upcoming physical task. Mental fatigue not having an effect on motivation is possibly explained by the differing natures of both tasks following upon each other. Inzlicht et al. [61] proposed a motivational shift model to explain that engaging in self-regulation at time 1 leads to declines in performance at time 2. However, while this model accounts for many relevant findings in the field, crossing over the nature of the task (e.g. a cognitive task followed by a physical task) might counteract the motivational shift (away from 'have-to' goals and towards 'want-to' goals) often observed when tasks of a similar nature follow each other (e.g. cognitive task after cognitive task) [62]. Higher perception of effort as the mediator of the negative effect of mental fatigue on physical performance also explains why mental fatigue does not impair maximal anaerobic tasks. The role of perception of effort in maximal anaerobic tasks is limited because of the all-out strategy that is employed. All-out strategies typically require no pacing and induce a faster build-up of peripheral fatigue (e.g. accumulation of metabolites).

2.6.3 How does mental fatigue increase perceived exertion during endurance performance?

Perceived exertion, also referred to as perception of effort, can be defined as the conscious sensation of how hard, heavy, and strenuous a physical task is. So far, three different theories have been suggested on which neural signal(s) are processed by the brain to generate the perception of effort [40]: (i) the afferent feedback from the working muscles and other peripheral physiological systems (i.e. the afferent feedback model [63]); (ii) the corollary discharges (neural signals from premotor/motor areas to sensory areas of the brain) associated with the central motor command (i.e. the corollary discharge model) [64-67]; (iii) a combination of afferent feedback and corollary discharges (i.e. the combined model [68]). It should be noted that recent evidence provides support in favour of the corollary discharge model (for more details please see [66, 69-71]). Yet without wishing to extend this discussion much further, it can be stated that perception of effort could possibly be increased by 1) increasing the intensity of afferent feedback from peripheral physiological systems, 2) increasing the intensity of central motor command (i.e. motor-related cortical activity) and thus its corollary discharges and 3) altering the processing of these neural signals in the brain (independently whether they originate from the periphery or from corollary discharges of the central motor command). The first option has been shown multiple times not to be influenced by mental fatigue, i.e. mental fatigue does not alter the physiological responses to exercise thought to provide afferent feedback to the brain (see section 4.2 Physiological). Regarding the second possibility, Pageaux et al. [20] demonstrated that mental fatigue was associated with a higher EMG root mean square of the vastus lateralis during cycling. This suggests that alterations in motor control may force mentally fatigued subjects to increase their central motor command and muscle recruitment (as shown by the increase in EMG amplitude) in order to produce the same power output even when central and peripheral fatigue are not exacerbated. This altered EMG amplitude due to mental fatigue has however to be confirmed by other studies. Furthermore, EEG should be used to directly test this hypothesis because central motor command can change even in the absence of changes in EMG amplitude [69]. The third option, an altered brain processing of the neural signals underlying perception of effort (independently whether they originate from peripheral receptors or premotor/motor areas of the cortex appears to be a reasonable explanation. However, we are not aware of any study who has tested this hypothesis.

2.6.4 A potential role for brain neurotransmitters

The importance of brain neurotransmitters in endurance performance has already been underlined by Roelands et al. [72]. They showed that reboxetine (a noradrenaline re-uptake inhibitor) decreased whole-body endurance performance in normal and high ambient temperature. Interestingly, despite a decreased power output during the time trial in this study there was no change in absolute RPE values, consequently increasing the RPE to power output ratio (meaning less power output is generated for a same RPE value). The intake of methylphenidate [73] [a dopamine (DA) reuptake inhibitor] in contrast allowed subjects to maintain a higher power output and improve time trial performance in the heat, again without influencing absolute RPE values. This demonstrates that altered brain neurotransmission is able to affect whole-body endurance performance and that this effect is associated with an altered RPE to power output ratio (in the case of DA, a decreased ratio). Klass et al. [74] showed that muscle endurance performance is affected in a similar way. A noradrenaline reuptake inhibitor reduced endurance time by 15.6 %. This was associated with a greater rate of supraspinal impairment and increase in RPE. Participants experienced the same intensity of intermittent contractions as harder to perform after administration of a noradrenaline reuptake inhibitor, without affecting the fatigue-related intramuscular impairments [74]. Pageaux et al. [17, 20, 35] stated that neural activity increases the extracellular concentration of adenosine (an inhibitory neurotransmitter; [75]) and that brain adenosine accumulation reduces endurance performance [76]. Subsequently they speculated that adenosine accumulation in the pre-supplementary motor area and anterior cingulate cortex (due to a mentally fatiguing task) could also explain in part the higher than normal perceived exertion during an endurance exercise in a mentally fatigued state. However, there is to date no study that demonstrates that mentally fatigued individuals have increased adenosine in specific areas. Moreover, other possible neurotransmitters that could mediate the effect of mental fatigue must not be overlooked. Hopstaken et al. [13] monitored certain psychophysiological markers of locus coeruleus activity during a mentally fatiguing task and reported that these markers (P3 and pupil diameter) were affected by the time-on-task manipulation. Consequently this indicates that the locus coeruleus (i.e. a nucleus in the brainstem responsible for the release of cortical noradrenaline) is also a possible mediator of the effects of mental fatigue [13]. Moeller et al. [77] investigated the role of DA in mental fatigue and concluded that also the dopaminergic midbrain is involved in sustaining motivation during fatigue. Research on neurological disorders and the often associated feelings of fatigue, also points towards an important role for the midbrain and other subcortical regions [78]. The above points out that most probably it will not be one particular neurotransmitter that mediates the negative effect of mental fatigue on endurance performance. Rather mental fatigue will affect neurotransmitter systems in multiple brain regions and the summation of these alterations might explain (in part) the impairment in endurance performance.

2.6.5 Future directions

Evidence from fields other than physical performance has already demonstrated that manipulation of neurotransmitter systems could reduce the negative effects of mental fatigue [77, 79]. Moeller et al. [77] used methylphenidate (i.e. a DA reuptake inhibitor) in order to manipulate the concentration of DA in the brain and assess what effect this had on the development of mental fatigue during a cognitive performance task. Similar interventions could be employed to assess the role of the above mentioned neurotransmitters in the mental fatigue/physical performance interaction. Almost 20 years ago, Caldwell et al. [79] reported that administration of dextroamphetamine (i.e. an indirect dopamine agonist) improved flight performance during the final 23 hours of a 40-hour period of continuous wakefulness. Similar studies investigating the effect of mental fatigue on physical performance could enlarge our knowledge of the role of different neurotransmitters in this interaction. Simultaneously more applied areas need further investigation as well. The cognitive tasks used to induce mental fatigue in the reviewed studies do not entirely resemble tasks (e.g. interviews, emotion control, and tactical meetings) that would regularly occur prior to competition. The mental fatigue induced by the cognitive demands of the competition itself should also be investigated. Finally, the impact of mental fatigue should be assessed on endurance performance of longer duration (e.g. marathon) and in high-level athletes, as it is likely that they may have superior ability to maintain performance [80].

2.7 Conclusion

Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity and is characterized by a combination of specific subjective, behavioural and physiological manifestations. Recent research has observed the effect of mental fatigue on physical performance. The current systematic review aimed at unravelling whether mental fatigue impairs physical performance and sought to create an overview of the potential factors underlying this effect.

Eleven articles on the topic were selected and the main outcome was a decline in endurance performance (decreased time-to-exhaustion and self-selected power output/velocity or increased completion time) due to mental fatigue, associated with a higher than normal perceived exertion. Physiological variables traditionally associated with endurance performance (heart rate, blood lactate, oxygen uptake, cardiac output, VO_2) were not directly affected by mental fatigue during and after endurance performance. Maximal strength, power and anaerobic work were not affected by mental fatigue. This led to the conclusion that duration and intensity of the physical task appear to be important factors in the decrease in physical performance due to mental fatigue.

Practically these findings suggest that a higher-than-normal perception of effort and reduced endurance performance are respectively a psychological and behavioural marker of mental fatigue. In addition, engagement in mentally demanding tasks before competitions requiring endurance should be avoided in order to optimize performance. Moreover, the high cognitive demands of sport are most probably mentally fatiguing when prolonged over time. This opens new opportunities to improve endurance performance by minimizing as much as possible the cognitive load during competitions and/or by increasing resistance to the negative effects of mental fatigue on perception of effort and endurance performance.

Compliance with Ethical Standards

Jeroen Van Cutsem, Samuele Marcora, Kevin De Pauw, Stephen Bailey, Romain Meeusen and Bart Roelands declare that the systematic review complies with all ethical standards.

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Conflicts of Interest

Jeroen Van Cutsem, Samuele Marcora, Kevin De Pauw, Stephen Bailey, Romain Meeusen and Bart Roelands declare that they have no conflicts of interest relevant to the content of this review.

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Chapter 3: Mental fatigue and the heat-induced decrease in endurance performance

Part 1: Mental fatigue and cycling performance in the heat

Effects of mental fatigue on endurance performance in the heat

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3.1.1 Abstract

Purpose: Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity and has been observed to decrease time-trial (TT) endurance performance by ~3,5% in normal ambient temperatures. Recently it has been suggested that heat may augment the negative effect of mental fatigue on cognitive performance, raising the question whether it may also amplify the effect of mental fatigue on TT-performance. **Methods:** In 30 °C and 30% relative humidity, ten endurance-trained male athletes (Age: 22 ± 3 y; W_{max}: 332 ± 41 W) completed two experimental conditions: intervention (I; 45-min Stroop task) and control (C; 45-min documentary). Pre and post intervention/control, cognitive performance was followed up with a 5-min Flanker task. Thereafter subjects cycled for 45 min at a fixed pace equal to 60%-W_{max}, immediately followed by a self-paced TT in which they had to produce a fixed amount of work (equal to cycling 15 min at 80%-W_{max}) as fast as possible. **Results:** Self-reported mental fatigue was significantly higher after I compared to C ($P<0.05$). Moreover electroencephalographic measures also indicated the occurrence of mental fatigue during the Stroop ($P<0.05$). TT-time did not differ between conditions (I: 906 ± 30 s, C: 916 ± 29 s). Throughout exercise, physiological (heart rate, blood lactate, core and skin temperature) and perceptual measures (perception of effort and thermal sensation) were not affected by mental fatigue. **Conclusion:** No negative effects of mild mental fatigue were observed on performance and the physiological and perceptual responses to endurance exercise in the heat. Most plausibly mild mental fatigue does not reduce endurance performance when the brain is already stressed by a hot environment.

Key words: exercise, whole-body endurance performance, heat, effort

3.1.2 Introduction

Physical performance and more specifically endurance performance is negatively affected by mental fatigue (see Van Cutsem et al. [1] for a systematic review on the topic). Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity and is characterized by various subjective, physiological and behavioural alterations. It is manifested as an acute increase in subjective ratings of fatigue [2-5], specific electroencephalography (EEG) alterations [3, 6, 7] and/or an acute decline in cognitive performance [2, 5]. Often it is induced by a response inhibition task (e.g. incongruent Stroop task) that requires self-control to inhibit automatic responses to certain stimuli. Prolonged performance on such a task prior to endurance exercise leads to higher perception of effort and impaired endurance performance [1]. A higher perception of effort manifests itself as a higher rating of perceived exertion (RPE) during fixed workload tests, whilst during time trials the workload is lower relative to RPE. Physiological parameters like respiratory, cardiovascular, metabolic or neuromuscular function during and after endurance exercise [2, 5, 8] do not seem to be influenced by mental fatigue.

Heat stress is also known to impair endurance performance [9, 10]. The impairment in performance has frequently been associated with a rise in cardiovascular strain [9] during endurance exercise, a decrease in maximal aerobic capacity, a higher internal body temperature (T_{core}) , higher skin temperature (T_{skin}) [11], hypohydration [11], neuromuscular changes within the central nervous system [12] and an altered metabolic profile in the activity-dependent muscle groups [13]. Apart from all these physiological alterations during exercise in the heat, perceptual responses [thermal sensation (T_{sens}), thermal comfort and perception of effort] are also affected. Traditionally the effects of heat on these perceptual responses have been explained as a consequence of the increased physiological strain [11]. However, we still do not know why perception of effort is higher during exercise in the heat. This could be due to the increased physiological strain, but direct effects of heat on the brain could also be the cause [14]. Similarly, we do not know why perception of effort during exercise is higher in mentally fatigued individuals [1]. However, we can exclude physiological strain [2] and neuromuscular fatigue [15] as there have been no differences observed in these parameters due to mental fatigue. This underlines that the mechanisms causing the higher perception of effort during exercise in conditions of mental fatigue and heat are currently largely unknown. If the mechanisms between the two stressors differ, then one mechanism could add to the other and cause perception of effort to raise further and consequently deteriorate endurance performance even more.

Qian et al. [16] were one of the first to combine both mental fatigue and heat. After thermal exposure [normothermic (25 °C, 1 h) and hyperthermic condition (50 °C, 1 h)], twenty participants performed a twenty-minute psychomotor vigilance test while task-related cerebral blood flow was being registered in a scanner. This revealed that prior heat stress has a potential fatigue-aggravating effect while performing a task demanding continuous attention. They observed a decreased resting-state cerebral blood flow in the fronto-parietal cortex after the heat exposure compared to a thermoneutral situation. This was associated with subsequent slower reaction times, consequently indicating heat may accelerate the occurrence of mental fatigue. The fronto-parietal cortex is an area in the brain that encompasses multiple regions (e.g. dorsolateral prefrontal cortex (DLPFC), anterior prefrontal cortex (APFC) and somatosensory association cortex (SAC)). Specific changes in brain-activity in this part of the cortex have frequently been associated with an impaired cognitive performance and mental fatigue [6, 7, 17, 18].

From the above it is clear that mental fatigue impairs endurance performance and that heat stress may accelerate the occurrence of mental fatigue. Heat stress might augment the effect of mental fatigue on endurance performance by aggravating the mental fatigue induced by a given prolonged demanding cognitive task and/or by affecting perception of effort through a different and additive mechanism. Therefore the main aim of this study was to examine whether mental fatigue decreases subsequent endurance performance in the heat as measured by a time trial (TT). Such TT protocols have been shown to have a high reproducibility [19]. Before the self-paced TT we included a fixed-workload period to accentuate fatigue in the heat and better quantify the effects of mental fatigue on physiological and perceptual responses to endurance exercise. From a more applied point of view, this endurance task simulates many cycling races in which a peloton covers the first three quarters of a race at a slower pace than the last quarter. Additionally it would be useful to know whether mental fatigue exerts the same negative influence on endurance performance in warm conditions as has been observed in normal ambient temperatures (5% [20] and 2% [4] decrements). Therefore this study provides useful insights for athletes competing in major sport events like the 2022 (in Qatar) FIFA World Cup and the 2020 Olympic Games in Japan that take place in such a warm climate.

We hypothesized mental fatigue would be induced in the heat, characterized by subjective (higher ratings of mental fatigue [2, 3, 5]), neurophysiological (lower P3b-amplitude [7, 17] and higher fronto-parietal theta (θ)- and alpha (α)-activity [6, 18] due to mental fatigue) and behavioural measures (decreased accuracy and increased reaction time (RT) in time due to mental fatigue [2, 5]). Mental fatigue would subsequently negatively affect performance on the endurance task in the heat. More specifically we expect a higher perception of effort during the 45-min fixed workload part, whilst the time trial (TT) would take longer to complete due to mental fatigue [2-4]. We also expected a bigger decrease in TT-performance due to mental fatigue in heat than the impairments observed in normal ambient temperatures (~3.5%) [4, 20].

3.1.3 Methods

3.1.3.1 Subjects and ethical approval

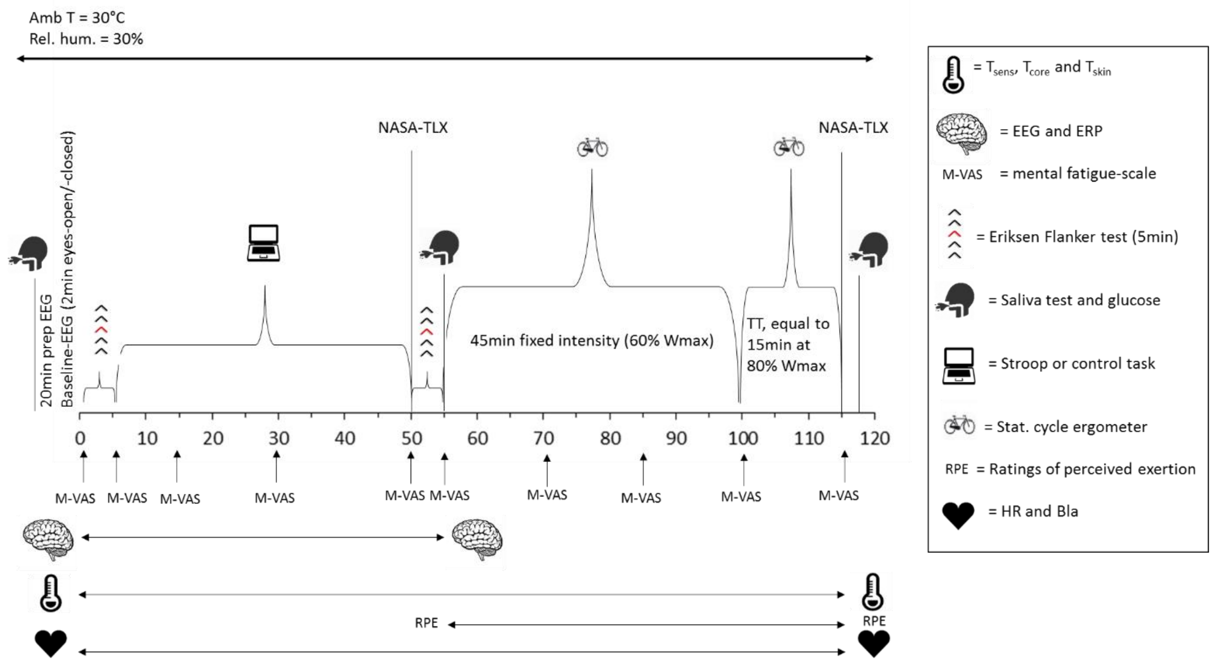
Ten trained male cyclist or triathletes (mean ± SD; age: 22 ± 3 y, height: 184 ± 4 cm, weight: 74 ± 7 kg, W_{max}: 332 ± 42 W) volunteered to participate in this study. None of the subjects had any known mental or somatic disorder. Our subjects can be included in the performance level 3 in the classification of subject groups in sports science research [21]. Each subject gave written informed consent prior to the study. Experimental protocol and procedures were approved by the Research Council of the Vrije Universiteit Brussel, Belgium. All subjects were given written instructions describing all procedures related to the study but were naive of its aims and hypotheses.

3.1.3.2 Experimental protocol

On the first visit to the lab subjects underwent a medical examination by a physician. Subjects were excluded if they presented with any medical history, family history or medication or drug use that would prevent them from safely completing the experiment. Subjects then completed a maximal cycle ergometer test to determine the maximal wattage (W_{max}). This maximal exercise test was conducted progressively on a cycle ergometer (Lode Excalibur Sport, Groningen, the Netherlands) in order to determine W_{max} as accurately as possible: the test started at 80 W for 3 min, thereafter the resistance was increased by 40 W each 3 min until exhaustion. The W_{max} was calculated with the formula: $W_{max} = W_{out} + (t/180) \times 40$ [W_{out}: workload of the last completed stage; t: time (seconds) in the final stage]. Before the incremental test the position on the cycle ergometer was adjusted for each subject, and settings were recorded and reproduced at each subsequent visit. Subjects were also given standard instructions for overall RPE using the 15-point scale (6-20) developed by Borg [22]. During the incremental exercise test, the scale low and high anchor points were established. In order to acquaint participants with the feelings of exertion that should be rated 7, they were asked to cycle unloaded at 50 rpm for 3 min before the start of the incremental exercise test. To establish the high anchor point participants were asked to assign a rating of 19 to the conscious sensations of how hard, heavy, and strenuous exercise felt at the end of the incremental exercise test.

The subjects were asked to return to the lab for 3 consecutive trials, which were all conducted in the morning and were separated by at least 5 days to ensure full recovery. The first trial was a familiarization trial (to get to know the routine, the equipment and to avoid learning effects), followed by an intervention trial and a control trial in a randomized and counterbalanced order (www.randomization.com). All trials were conducted in 30 °C and in a relative air humidity of 30 %. In both the intervention and the control trial subjects performed a 45-min cognitive task, either involving response inhibition (Stroop task) or a control task (see *Cognitive tasks* section). In the familiarization trial subjects completed only 15 min of the 45-min Stroop task. Preceding the beginning of the 45-min cognitive task, a urine sample was taken, the subjects' body mass was measured and all physiological measuring instruments were applied (see *Physiological and psychological measurements* section). After the 45-min cognitive task, subjects performed 45 min of moderate intensity cycling exercise at a fixed workload immediately followed by a self-paced time trial (TT; see *Endurance task* section). Heart rate (HR) and thermoregulatory measures were followed up at 5-min intervals throughout the entire protocol and RPE at 5-min intervals during the endurance task (see *Physiological and psychological measurements* section). Cognitive performance was tested before and after the 45-min cognitive task using a Flanker task (see *Cognitive tasks* section). Brain activity was measured during the 45-min cognitive task (see *EEG recordings* section). Self-reported mental fatigue was assessed with a visual analogue scale (M-VAS) before and after the Flanker tasks, during the 45-min cognitive task and during the endurance task (see *Physiological and psychological measurements* section). Subjective workload was assessed after the 45-min cognitive task and after the endurance task (see *Physiological and psychological measurements* section). Blood glucose levels and salivary concentration of cortisol were assessed before and after the Flanker tasks and salivary cortisol concentrations were measured again after the endurance task (see *Physiological and psychological measurements* section). An overview of the experimental protocol performed during the intervention and the control trial is presented in Fig. 1.

Fig. 1 Overview of the protocol depicted on a timeline (min).



The subjects were given instructions to sleep for at least 7 hours, refrain from the consumption of caffeine alcohol and not to practice vigorous physical activity 24 hours before each visit. In addition subjects were asked to have the same meal the night before and the morning of each trial and the use of any kind of medicinal products during and between the trials was prohibited. If subjects could not meet these standards they were excluded from the study. To facilitate the contact between the EEG-electrodes and the subjects' head, they were also asked to wash their hair (with neutral soap) the evening before the experiment.

To ensure high motivation during the Stroop task and the TTs, a reward was given to the best mean performance in the Stroop task (€50) and in the TTs (€50).

3.1.3.3 Cognitive tasks

The 45-min tasks used as experimental manipulation in the present study are similar to those used by Smith et al. [23]. A 50%-incongruent Stroop task and a documentary were used respectively for the mentally fatiguing task and the control task [23]. A brief description of these cognitive tasks can be found below.

Stroop task

The Stroop task requires response inhibition which is a form of inhibitory control. In this task, coloured words ("red", "blue", "green" and "yellow") were presented one at a time on a computer screen and participants were required to indicate the colour of the word, ignoring the meaning of the word itself. The trials were arranged in pseudo-random sequence with 50% of trials being congruent (matched word and colour), while 50% were incongruent, with all incongruent word-colour combinations being equally common. Participants were required to press the button on the keyboard that corresponded to the colour of the word displayed on screen. Each word was presented on screen in font size 34 for 1000 ms followed by a blank screen for 1500 ms before the next word was displayed. Therefore a new word was presented every 2500 ms providing a total of 1080 stimuli over the 45-min task. Each 15 min there was a 30-s break in the task to assess M-VAS and T_{sens}. Subjects were instructed to respond as quickly and accurately as possible and were aware that points would be awarded on both performance measures for the €50-prize.

Control task

The control task involved watching a 45-min documentary on the same computer screen as the one used for the Stroop task. The documentary used in this study was “When We Left Earth: The NASA Missions – Episode 6: A Home in Space” (Discovery Channel, USA). The content of this documentary has shown in a previous study [23] to be engaging, yet capable of maintaining a neutral mood and not to induce mental fatigue. In order to prevent sound-artefacts occurring in the EEG recordings (*see EEG recordings*), subjects watched the documentary without sound. Every 15 min, subjects refrained 30 s from watching the documentary while M-VAS and T_{sens} were assessed.

Flanker task

To assess the influence of the 45-min tasks on cognitive performance independently from time-on-task a modified Flanker task, identical to the one used by Weng et al. [24], was used. This task was chosen because, similar to the Stroop task, it requires inhibitory control [24]. The congruency of the flanking items to the target arrows was manipulated in the modified Flanker task, resulting in three conditions: congruent (e.g. > > > > >), incongruent (e.g. < < > < <) and neutral (e.g. - - > - -). Each array of arrows was focally presented in white text (font size 34) for 200ms on a black background with a variable inter-stimulus interval of 1000, 1200, 1400, or 1600 ms. For each of the task conditions, 40 trials were presented randomly with right and left target arrows occurring with equal probability, yielding a total of 120 trials. Total Flanker task duration was approximately 5 min. To assess performance on the Flanker task accuracy and RT were collected and participants were instructed to respond as quickly and accurately as possible to the direction of a target arrow while ignoring two flankers on each side.

3.1.3.4 Endurance task

Subjects had to perform 45-min cycling at 60% W_{max}, immediately followed by a TT that requires the subjects to complete a predetermined amount of work equal to 15 min at 80% W_{max} as quickly as possible. Throughout the endurance task subjects were not verbally encouraged by the experimenter to ensure no bias occurred in motivating subjects. Subjects performed the task on an electromagnetically braked cycle ergometer (Excalibur Sport, Lode, Groningen, The Netherlands) and had ad libitum access to plain non pre-cooled water.

45-min fixed workload part

During the 45-min fixed workload part, the cycle ergometer was set in the hyperbolic mode so that the workload (60% W_{max}) was independent of pedalling rate (RPM). Cadence was freely chosen between 60 and 120 RPM. Feedback on elapsed time, RPM, power output and HR was not available to the subject.

Self-paced time trial part

One to two min (to program the TT-protocol) after the 45-min fixed workload part of the endurance task, the self-paced TT began. Similar to the initial part, the cycle ergometer was set in hyperbolic mode. As stated above, the TT required the subjects to complete a predetermined amount of work equal to 15 min at 80% W_{max} as quickly as possible. Subjects began the TT at a workload corresponding to 80% W_{max}, but were free to in- or decrease their power output as desired from the outset. If subjects indicated (orally) they wanted to in- or decrease their power output, the experimenter respectively increased or decreased the workload by a standardized amount of 5 W. Again cadence was freely chosen between 60 and 120 RPM and subjects only received feedback regarding RPM if they dropped below or above the given interval. Furthermore no feedback was provided regarding power output or HR. However they did get feedback regarding the amount of work produced in relation to their goal (equal work to 15 min at 80% W_{max}). Therefore a graph was displayed where the amount of work was depicted on the y-axis and on the x-axis the amount of time elapsed. Subjects were instructed to produce the predetermined amount of work as quickly as possible and were aware that mean performance on the TT was scored for the €50-prize.

3.1.3.5 Physiological and psychological measurements

Heart rate

Heart rate was recorded continuously (followed up at 5-min intervals) throughout the entire protocol using a HR monitor (Polar RS400, Polar Electro Oy, Kempele, Finland).

Hydration status and body mass

A urine sample was taken and analysed for specific gravity (pocket refractometer; Atago, Japan) preceding the start of the protocol and at the end of the protocol. If a hydration status higher than 1.020 was observed, subjects were instructed to drink ~20cl of water to prevent them from starting the protocol in a too dehydrated state. Body mass was also measured before and after the protocol to observe weight loss or gain. As the subjects had ad libitum access to plain water during the protocol the amount of water drunk was also measured to take this into account.

Thermoregulatory measures

During the entire protocol, thermoregulatory measurements were recorded every 5 min. To measure T_{core}, subjects inserted a rectal thermistor 10 cm beyond the anal sphincter (Gram Corporation LT-8A, Saitama, Japan). Skin temperature probes (Gram Corporation LT-8A, Saitama, Japan) were attached to four sites (chest, upper arm, thigh and calf). Subsequently mean weighted skin temperature (T_{skin}) was measured according to the method described by Ramanathan [25]. T_{sens}, the subjective feeling of heat, was assessed using a 21-point scale ranging from unbearable cold to unbearable heat.

Blood lactate and glucose

Capillary blood was collected at the ear lobe for the determination of blood lactate ([Bla]) (determined enzymatically; EKF; BIOSEN 5030, Magdeburg, Germany). [Bla] levels were measured before and after the 45-min task, during the endurance task (at 5-min intervals) and after the endurance task.

Salivary cortisol

Saliva was used to test for cortisol responses due to its ease of compliance, low invasiveness, and ability to track the biologically active "free" hormone. Saliva (2ml) was collected by passive drool into sterile containers, and these were stored at −80 °C until assay. A saliva sample was taken before the 45-min task, after the 45-min task and after the endurance task. After visual inspection for blood contamination, the saliva samples were analysed in duplicate using the “Cortisol II” test of Roche on the Cobas e601 analyser.

Self-reported mental fatigue

Self-reported mental fatigue was measured using M VAS before, during (every 15 min) and after the 45-min task, during (every 15 min) and after the endurance task. Participants were asked to indicate their perceived level of mental fatigue (from not at all to completely exhausted) by placing a mark on a 10-cm line.

Perception of effort

During the endurance task, perception of effort was measured at the beginning and each five minutes thereafter using the 15-points RPE scale [22] anchored during the incremental exercise test.

Subjective workload

The National Aeronautics and Space Administration Task Load Index (NASA-TLX [26]) was used to assess subjective workload. Participants completed the NASA-TLX after the 45-min task and after the endurance task in accordance with a study of Pageaux et al. [15].

3.1.3.6 Electroencephalographic recordings and analysis

During the 45-min task preceding the endurance task, brain activity was continuously measured. 32 active Ag/AgCl electrodes were attached on the subjects’ head (Acticap, Brain Products, Munich, Germany), according to the “10–20 International System” . The sampling rate was set at 500 Hz (Brain Vision Recorder, Brain Products, Munich, Germany). Electrode impedance was kept <10 kΩ throughout the recording. Baseline measurements were taken 2 min with eyes open, 2 min with eyes closed and subjects were seated in a dim lit room. During EEG recordings, subjects were seated, inserted earplugs and had been instructed to minimize movement of the head and eye blinking, to avoid frowning, to maintain the same posture and not to touch their head with their hands in order to minimize movement, sound and muscle artefacts.

ERP analysis The program Brain Vision Analyzer (version 2.1) was used to pre-process and process the data sets. Raw data were down-sampled to 256 Hz, filtered (high pass 1 Hz, low pass 45 Hz and Notch, Slope 48 dB/oct) with a Butterworth filter design and re-referenced to an average reference. For each data set of interest (i.e. ERP during the first, middle and last 15 min of the Stroop task) artefacts were semi-automatically removed. Then the different stimuli (congruent=S3; incongruent S5) were extracted from the EEG data sets. For stimulus locked ERP analysis, a data window was set at -200 to 800 ms relative to stimulus onset. Trials in which performance errors occurred were excluded. For each ERP epoch, independent component analysis (ICA) and inverse ICA further reduced artefacts. Furthermore, a baseline correction was applied (period -200 to 0 ms). Epochs were then averaged and the visually evoked potentials, P2, N2, P3b were assessed. Peak amplitudes and onset latencies were measured for the P2, N2 [inferior/orbitofrontal cortex (F7), broca’s area (mean of electrodes FC6 and F8), dorsolateral prefrontal cortex (mean of electrodes F3, Fz and F4), anterior prefrontal cortex (mean of electrodes FP1 and FP2), premotor cortex (mean of electrodes FC1 and FC2)] and P3b [somatosensory association cortex (SAC; Pz), angular gyrus (AG; mean of electrodes P3 and P4), fusiform gyrus (FFG; mean of electrodes P7, P8, PO9 and PO10)] components in their specific region of interest (ROI). The P2 is known to be frontally distributed [27] and was therefore analysed in the frontal ROI, it has been related to attentive stimulus evaluation or the recall of task rules [28]. The P2 was defined as the largest positive-going peak occurring within the time window between 150 and 250 ms. The N2 is usually interpreted as an index of conflict monitoring [29] and emerges fronto-centrally after the P2 [27], thus also for the N2 the frontal ROI were analysed. The N2 was defined as the largest negative-going peak occurring within the time window between 250 and 400 ms. The P3b is linked to salience processing and appears to occur when subsequent attentional resource activations promote memory operations in temporal-parietal areas [30], therefore the FFG, the AG and the SAC were analysed to observe any effects on the P3b. The P3b was defined as the largest positive-going peak occurring within the time window between 200 and 450 ms. Thereafter, the data from Brain Vision Analyzer was exported to SPSS (version 22.0; SPSS, Chicago, IL) for further analysis.

Spectral/power analysis Similar to the ERP analysis, the program Brain Vision Analyzer (version 2.1) was used to pre-process and process the data sets for the analysis of the total power. Raw data were down-sampled to 256 Hz, filtered (high pass 1 Hz, low pass 45 Hz and Notch, Slope 48 dB/oct) with a Butterworth filter design and re-referenced to an average reference. For each data set of interest [i.e. Continuous EEG measurements during both 45-min tasks (first, middle and last 5 min)] artefacts were semi-automatically removed. For each continuous EEG data set of interest segments with a length of 4 s and with an overlap of 2 s were extracted [6]. Subsequently ICA and inverse ICA further reduced artefacts. The resulting data segments were tapered with a Hanning window with 10% of the total segment length. FFT power spectra with a spectral resolution of 0.25 Hz were calculated for both sides of the spectrum, resulting in FFT segments containing the full spectral information. The resulting FFT segments were averaged to stabilize the spectral content. The power in the FFT was extracted for theta (θ, 3.5–7.5 Hz), alpha (α1, 7.5–10 Hz; α2, 10–12.5 Hz) and beta (β1, 12.5–18 Hz; β2, 18–35 Hz) in each ROI mentioned in the ERP analysis with the addition of the primary motor cortex (mean of electrodes C3, Cz and C4).

3.1.3.7 Statistical analysis

All data are presented as means ± standard deviation (SD) unless stated otherwise. The one-sample Kolmogorov-Smirnov test was used to test the normality of the data, sphericity was verified by the Mauchly's test. When the assumption of sphericity was not met, the significance of F-ratios were adjusted with the Greenhouse-Geisser procedure. Paired t-tests were used to assess the effect of condition (intervention vs. control) on mean HR during both 45-min tasks, and on NASA-TLX scores after the 45-min task, and after the endurance task. The effects of condition and time on salivary cortisol were analysed with two-way repeated measure (2 x 3) ANOVAs. Two-way repeated measure (3 x 2) ANOVAs were used to test the effect of time (first, middle and last 15 min) and stimuli (congruent and incongruent) on response accuracy and RT during the Stroop task. Two-way repeated measure (2 x 4) ANOVAs were used to test the effects of condition and time on M-VAS during the 45-min task and during the fixed workload part of the endurance task, during the self-paced part a paired t-test was employed to test the effect of condition. For the EEG-data (θ, α1, α2, β1, β2) three-way repeated measure (2 x 3 x 9) ANOVAs were employed with condition, time and ROI as factors. The different ERP-components (P2, N2 and P3b) were also analysed with a three-way repeated measure ANOVA with factors time, stimulus-type and ROI. Three-way repeated measure (2 x 2 x 3) ANOVAs were used to test the effects of condition, time and stimuli on mean accuracy and RT during each Flanker task. Two-way repeated measure ANOVAs were used to test the effects of condition and time on HR, T_{core}, T_{skin}, RPE, T_{sens} and [Bla] during the fixed workload (2 x 10) and the self-paced part (2 x 3; time: 5 min, 10 min and end-point) of the endurance task. If significant interaction effects in the three-way or two-way repeated measure ANOVAs were observed, respectively two-way repeated measure ANOVAs or paired t-tests were performed in order to interpret the effect of condition (intervention vs. control) in each time interval. If no significant interaction effects were observed in the three-way or two-way repeated measure ANOVAs, main effects were immediately observed and further interpreted through pairwise comparisons with Bonferroni correction. Significance was set at 0.05 for all analyses, which were conducted using the Statistical Package for the Social Sciences, version 22 (SPSS Inc., Chicago, IL, USA).

3.1.4 Results

3.1.4.1 Markers of mental fatigue

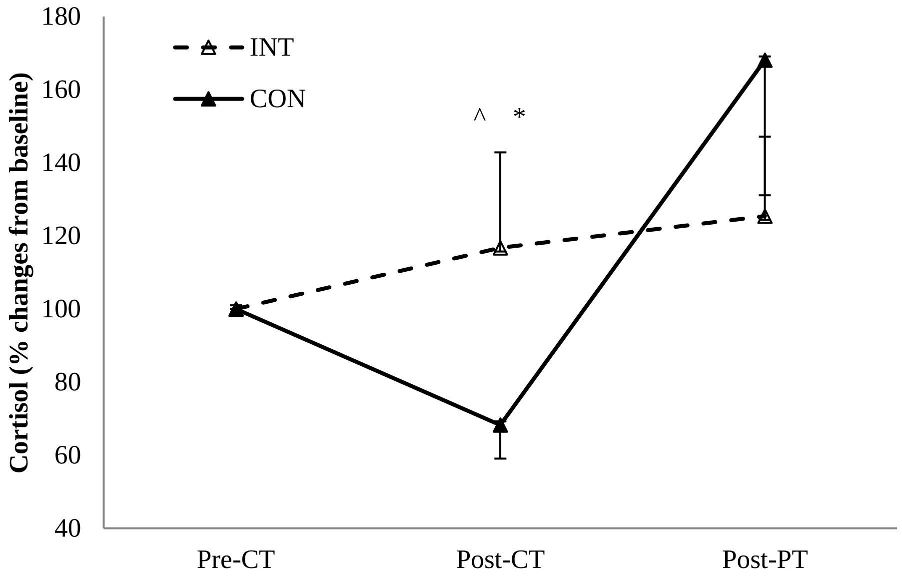
Various physiological, subjective and behavioural markers

Mean HR did not differ during the Stroop task (69 ± 8 beats/min) compared to the control task (67 ± 6 beats/min). The data of the NASA-TLX were not normally distributed and therefore Wilcoxon Signed Ranks Tests were employed. This revealed that 5 out of 6 subscales were perceived as higher/more demanding after the Stroop task compared to the control task. Mental demand (p=0.005), temporal demand (p=0.007), performance (p=0.05), effort (p=0.005) and frustration (p=0.008) were perceived as higher, or worse in the case of performance, in the Stroop task. This subjective higher perceived demand of the Stroop task is confirmed by the cortisol data. Cortisol values were normalized to the value of the saliva sample taken at the beginning of each trial (=100%). An interaction between the condition- and the time-effect was displayed for the normalized cortisol data (F(2, 14)=7.5; p=0.006). Significantly higher cortisol levels were found after the Stroop task compared to after the control task (p=0.033; Fig. 2). Subjectively a higher self-reported mental fatigue was observed after 30 (p=0.006) and 45 min (p=0.002) in the Stroop task compared to in the control task. The accuracy and RT during the Stroop were normalized to the performance in the first 15 min of the task (=100%), however no decrements were observed (for absolute values, see Table 1).

Table 1. RT and accuracy during pre Flanker, first, middle and last 15 min of Stroop and post Flanker, independent of stimulus-type

	INT	**CON**	**INT**	**CON**
Block	**RT ± SD (ms)**	**RT ± SD (ms)**	**Accuracy ± SD**	**Accuracy ± SD**
Pre Flanker	413 ± 13	398 ± 10	0.97 ± 0.1	0.97 ± 0.1
Stroop: First 15 min	633 ± 20	//////////	0.85 ± 0.3	//////////
Stroop: Middle 15 min	632 ± 21	//////////	0.85 ± 0.4	//////////
Stroop: Last 15 min	625 ± 20	//////////	0.82 ± 0.4	//////////
Post Flanker	399 ± 9	379 ± 8	0.96 ± 0.1	0.96 ± 0.1

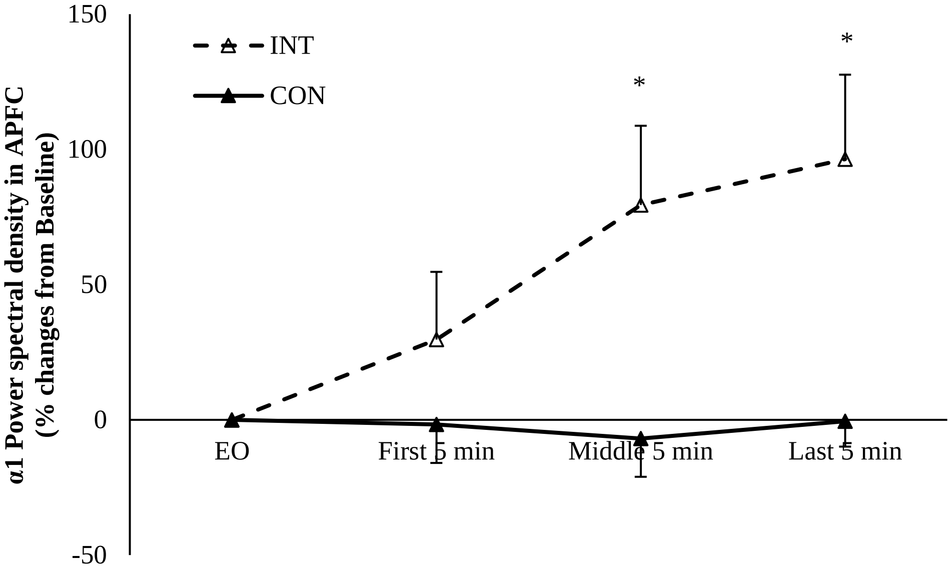
Fig. 2 Saliva cortisol levels before (pre-CT; pre 45-min task), after the cognitive task (post-CT; post 45-min task) and after the physical task (post-PT; post endurance task) in the intervention (INT) and control (CON). ^ denotes a significant difference compared to the previous time-point (p<0.05), * denotes a significant difference between conditions (p<0.05). Data are presented as means ± SE.



Spectral power analysis

The spectral power data of the first, middle and last 15 min of the Stroop task were normalized to the eyes open-condition before the beginning of the Stroop task (=0%) for each specific frequency band (θ, α1, α2, β1, β2). *θ*. No interactions were observed for θ-activity, it increased significantly in time (F(3, 27)=10.3; p<0.001) and was significantly higher (F(1, 9)=5.2; p=0.048) in the Stroop task (28 ± 5%) compared to in the control task (14 ± 5%). *α1*. The lower alpha band showed a significant main effect of time (F(3, 27)=4.1; p=0.017) and an interaction effect of condition with ROI (F(8, 72)=2.3; p=0.030). In the APFC a subsequent interaction of condition with time was observed (F(3, 27)=5.2; p=0.006). The follow-up paired t-tests showed that only in the middle and last 5 min α1-activity was higher in the Stroop task compared to the control task (p≤0.006; Fig. 3). In the other eight ROI no interaction of condition with time or main effect of condition was observed. *α2*. For the upper alpha band a significant interaction effect of condition with time was observed (F(3, 27)=4.6; p=0.010). A subsequent two-way repeated measure ANOVA (Cond x ROI) in each time interval revealed that in the middle and last 5 min of the cognitive task α2-activity was significantly higher in the Stroop task compared to the control task (F(1, 9)≥5.9; p≤0.037) independently from ROI. *β1*. The lower beta band-activity showed a significant increase in time (F(3, 27)=8.0; p=0.001), however no effect of condition or ROI was observed. *β2*. Similar for the upper beta band-activity only a significant increase in time was observed (F(3, 27)=5.7; p=0.004), condition or ROI again had no effect.

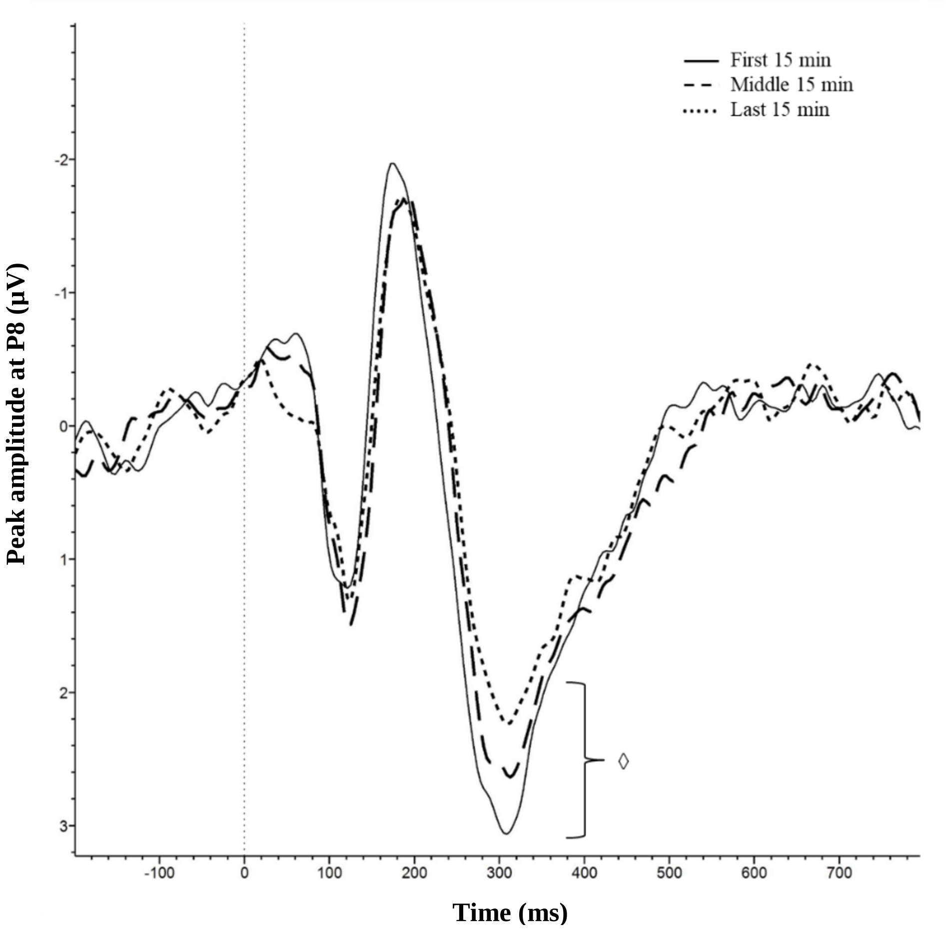
Fig. 3 α1 power spectral density during EO, first, middle, and last 5 min of the 45-min task in intervention (INT) and control (CON). *Significant difference between conditions (p<0.05). Data are presented as means ± SE.



ERP analysis

P2. No interaction effects for P2-amplitude or –latency and also no main effect of time or stimulus-type was observed. *N2*. No interaction or main effects were found for the N2-amplitude or -latency. *P3b*. The three-way ANOVA showed that the ROI- and time-effect on P3b-amplitude interacted with each other ($F(1.9, 17.3)=3.9$; $p=0.041$). To further unravel the time-effect, a two-way ANOVA (time x stimulus-type) was employed in each ROI. This revealed that amplitude only decreased over time in FFG ($F(2, 18)=4.4$; $p=0.027$; Fig. 4) from 3.9 ± 0.7 µV in the first 15 min to 3.2 ± 0.6 µV in the middle 15 min and 2.9 ± 0.5 µV in the last 15 min. In case of the P3b-latency no interactions between the different factors were found, a main effect of time was however present ($F(2, 18)=8.1$; $p=0.003$). There was an increase ($p=0.002$) in latency from the first (311.2 ± 10.9 ms) to the middle 15 min (327.8 ± 11.1 ms), where after it plateaued and even slightly decreased from the middle to the last 15 min (321.2 ± 12.8 ms).

Fig. 4 Grand average ERP at P8 elicited by all (congruent and incongruent) stimuli in the first 15 min, middle 15 min, and last 15 min during the Stroop task in intervention. ◊Significant main effect of time (P<0.05).



Flanker task

An interaction of condition with time was observed for M-VAS before and after each flanker task (F(1.8, 16.3)=13.4; p<0.001). In the intervention M-VAS was higher during the post-Flanker task (pre-Flanker: p=0.002; post-Flanker: p=0.001). This higher self-reported mental fatigue was however not associated with a deteriorated cognitive performance. The data for RT and accuracy were normalized to the baseline (i.e. the performance on the first Flanker task (=100%)) to account for day to day variability (for absolute values, see Table 1). In terms of RT, a main effect of time was observed (F(1, 9)=13.4; p=0.005). Subjects performed faster in the second (96 ± 1%) compared to the first Flanker task (100%) independent of stimulus-type or condition. For the accuracy-data to be normally distributed, the factor 'stimuli-type' was not accounted for and the mean of the three stimuli-types was used, subsequently the effect of condition and time was observed in a two-way ANOVA. Accuracy was found to decline in time (F(1, 9)=24.5; p=0.001) independently from condition. It dropped from the first (100%) to the second Flanker task (98.9 ± 0.2%; p=0.001). No interaction or main effect of condition was observed.

3.1.4.2 Physiological and psychological responses during the fixed workload part of the endurance task

Physiological responses

HR was not significantly altered in both conditions during the fixed workload part, in the intervention trial mean HR was 152 ± 2 bpm and in the control trial this was 152 ± 3 bpm. Non-parametric tests showed that there were no differences in [Bla] between conditions in any time interval throughout the fixed workload part. In both conditions [Bla] increased in the first 5 min ($Z \geq -2.5$, $p \leq 0.013$) and reached a plateau afterwards (intervention: 2.0 ± 1.0 mmol/L, control: 2.1 ± 0.8 mmol/L). T_{core} ($F(1.8, 14.6)=430.6$; $p<0.001$) and T_{skin} ($F(2.4, 21.4)=86.6$; $p<0.001$) rose throughout the fixed workload cycling part until 38.6 ± 0.3 °C and 36.3 ± 0.4 °C respectively. There was however no difference in T_{core} and T_{skin} between both conditions. T_{core} data of only 9 subjects were used in this analysis.

Perceptual responses

An interaction between condition and time was observed for M-VAS during the fixed part of the cycling task ($F(3, 27)=12.3$; $p<0.001$; Fig. 5). Self-reported mental fatigue was higher at the start and after 15 min in the fixed workload part of the cycling task in the intervention compared to control ($p \leq 0.012$; Fig. 5). RPE and T_{sens} data were not normally distributed, Wilcoxon tests pointed out that RPE (Fig. 6) and T_{sens} did not differ significantly in any time interval between both conditions.

Fig. 5 Self-reported mental fatigue during the fixed workload part of the endurance task, at the begin (P0), after 15 min (P15), after 30 min (P30), and at the end (P45). ^Significant difference compared with the previous time point (P<0.05). *Significant difference between conditions (P<0.05). Data are presented as means ± SE.

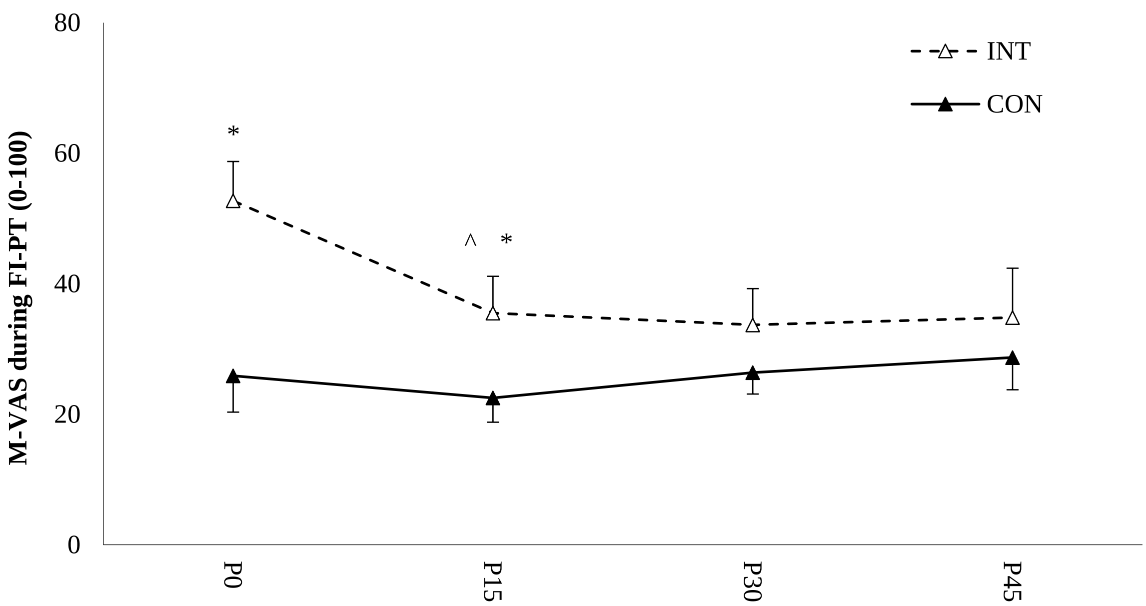
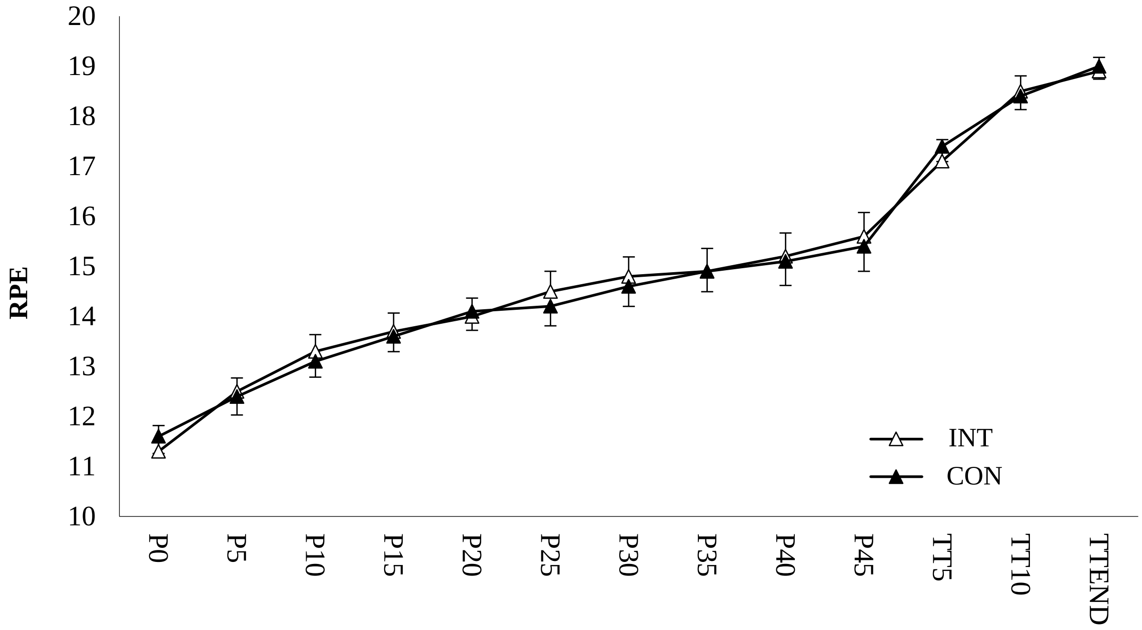


Fig. 6 Rating of perceived exertion during the endurance task in both conditions. At the begin (P0) of the fixed workload part, and at 5-min intervals throughout the fixed workload part and the time trial (TT) part. Data are presented as means ± SE.



3.1.4.3 Performance, and physiological and psychological responses during the self-paced time trial part of the endurance task

Endurance performance

The TT was completed in 906 ± 30 s in intervention and in 916 ± 29 s in control. These performances did not differ significantly from each other. The selected power output was, as the TT-time already indicated, similar in both conditions and decreased in time ($F(2.0, 17.6)=4.3$; $p=0.030$) independently from condition.

Physiological responses

HR ($F(1.2, 10.8)=46.8$; $p<0.001$), [Bla] ($F(2, 18)=24.1$; $p<0.001$) and T_{core} ($F(1.1, 8.9)=239.4$; $p<0.001$) increased significantly during the TT. At the end of the TT participants reached a mean HR of 186 ± 3 bpm, mean [Bla] of 7.1 ± 0.9 mmol/L and a mean T_{core} of 39.1 ± 0.1 °C. No interaction or main effect of condition was observed. Similarly, also for cortisol no effect of condition was observed before and after the endurance task.

Perceptual responses

M-VAS increased both in intervention ($p=0.045$) and in control ($p=0.011$) and neither at the start or at the end of the TT a significant difference in M-VAS between conditions was observed. The data of the NASA-TLX was not normally distributed, none of the subscales in relation to the endurance task were perceived differently between conditions. The RPE data had also to be tested non-parametrically, RPE increased significantly in both conditions during the TT ($Chi^2 \geq 14.1$; $p \leq 0.001$) and eventually reached a mean value of 19 ± 1 over all trials. No effect of condition was observed. T_{sens} increased significantly during the TT ($F(2, 18)=23.1$; $p<0.001$) up to 8.4 ± 0.4, no interaction or condition effect was however observed.

3.1.5 Discussion

This is the first study that looked at the effect of mental fatigue on endurance performance and cognitive performance in the heat (30°C) in performance level 3 [21] trained athletes.

Markers of mental fatigue

The importance of monitoring subjective, behavioural, and physiological markers of mental fatigue and the interactions between all three manifestation areas to conclude whether mental fatigue was induced or not has been highlighted in the review of Van Cutsem et al. [1]. In the present study we strived towards such a quantification of mental fatigue. Subjectively participants rated the Stroop task as more mentally demanding on the NASA-TLX. Physiologically, salivary cortisol levels were higher post-Stroop compared to post-control task, indicating that the Stroop task was more stressful than the documentary. The higher mental demand and stress during the Stroop task eventually resulted in the occurrence of mild mental fatigue. This was indicated subjectively by the higher M-VAS score and was further substantiated physiologically by the neurophysiological indices. Higher θ- and α2-activity was observed in the intervention compared to control throughout all the ROI in the middle and the last 5 min. α1-activity was specifically higher in the APFC during the middle and the last 5 min in intervention compared to control. A recent study of Wascher et al. [6], in which participants had to perform a spatial stimulus-response-compatibility task for an overall duration of 4 h, reported mental fatigue is specifically associated with an increase in frontal theta- (θ) and frontal and occipital alpha- (α) activity. These specific changes in brain-activity indicate a reduced level of arousal and subsequent attention deficits [18]. Also the ERP measures indicated mental fatigue was successfully induced. The P300 is a component of an ERP that appears around 300 ms after the onset of a stimulus and its amplitude is suggested to serve as an electrophysiological marker of attentional resource allocation, while its latency reflects the speed of stimulus evaluation [24]. Within the P300 a distinction can be made between the P3a that is linked to novelty detection and appears when non-target distractor stimuli are processed and the P3b that appears to occur when subsequent attentional resource activations promote memory operations in temporal-parietal areas [30]. In the FFG, a brain area known for object recognition and reading [31], the P3b-amplitude decreased in time, while the P3b-latency increased in time during the Stroop task in the present study. Käthner et al. [17] and Hopstaken et al. [7] both studied the P3b on the Pz-electrode (=an electrode in the parietal region) during a mentally fatiguing task and also found a decrease in P3b amplitude with increasing self-reported mental fatigue and time-on-task. Polich suggested [30] that the P3b is related to temporal–parietal activity, an area where dense norepinephrine inputs are found [30]. In addition he also associated P3b-amplitude with dopaminergic activity [32]. The associations Polich [30, 32] makes indicate that the altered P3b-amplitude and -latency observed in the present study suggest that altered neurotransmission (i.e. decreased norepinephrine- and dopamine-activity) has a role in the state of mental fatigue. Only behavioural measures did not substantiate that a state of mental fatigue was successfully induced. Contrary to other studies in the field [2, 5], no effect of time was observed in terms of accuracy or RT during the Stroop task. Despite not observing the typical decrease in accuracy and RT associated with mental fatigue, there are arguments to state mild mental fatigue was successfully induced and to expect a decrease in subsequent endurance performance similar to previous studies [2, 4, 5, 20]. Studies of Macmahon et al. [4] and Pageaux et al. [20] also did not observe a decrease in accuracy nor an increase in RT with prolonged performance on the mentally fatiguing task and still detected significant reductions in a subsequent endurance task due to mental fatigue.

The Flanker task was included in the study, as proposed in the review of Van Cutsem et al. [1], to be able to quantify cognitive performance independently from time-on-task effects during the Stroop task. In terms of performance on the Flanker task our data only partly confirmed this hypotheses. Accuracy during the Flanker task indeed decreased pre to post the Stroop task, but this was also the case pre to post the control task. The RT-data even contrasted our hypotheses. Instead of increasing, RT during the Flanker task decreased pre to post both 45-min tasks. A trade-off effect between RT and accuracy could possibly explain these results. Meaning that participants adapted their strategy within a trial and performed faster in the post-Flanker task while sacrificing accuracy. Besides a trade-off effect, switching between tasks could also have had a motivational effect that possibly masked a negative effect of mental fatigue on the Flanker task [33]. Another explanation could be that participants, despite a 30-min adaptation period to the environmental conditions, did not reach a steady baseline level when performing the pre-Flanker task. Subsequently the faster RT in the post-Flanker task can be explained as an adaptation-effect to the heat stress. This adaptation could also clarify why no higher RT during the Flanker task was observed with after the 45-min Stroop task. However this is rather speculative and because of the fact no effect of condition was found in RT or accuracy during the Flanker task, it was concluded to define the mental fatigue induced in this study as 'mild'.

Effects of mild mental fatigue on endurance performance in the heat

The endurance task consisted of two parts, a fixed workload part and a subsequent TT. During the fixed workload part, the effects of mild mental fatigue on physiological and perceptual measures could be more accurately assessed, while during the subsequent TT the effect of mild mental fatigue on endurance performance was evaluated. In order to monitor the state of mental fatigue during the fixed workload part of the endurance task, M-VAS was taken each 15 min. According to this measure, mental fatigue was higher during the intervention trial compared to control only in the first 15 min of the endurance task, and decreased thereafter. Contrary to our hypotheses the perceptual measures (i.e. perception of effort and T_{sens}) were not affected by this state of mild mental fatigue. The physiological data did confirm our hypotheses. HR and [Bla] were unaffected by the mild mental fatigue, confirming the findings of previous studies [2, 4, 5]. Moreover thermoregulatory measures, T_{core} and T_{skin}, during exercise in the heat were also unaffected by mild mental fatigue. This adds to the mounting evidence that mild mental fatigue indeed does not influence the traditional physiological responses thought to limit endurance performance. In the subsequent TT, pacing and performance time were the main variables of interest. Contrarily to our hypotheses, both performance time and pacing during the TT were unaffected by mild mental fatigue. Likewise the physiological and perceptual responses during the TT were unaffected. Multiple explanations for these diverging results compared to previous research [2-5, 20] are possible. First, performing the Stroop task for 45 min might have been insufficient to induce mental fatigue in an already stressful environment (i.e. in the heat). However multiple findings are presented (see *markers of mental fatigue*) in this study to support that mild mental fatigue was present, and to a similar extent, compared to previous studies [2, 4, 20]. A mentally demanding cognitive task as short as 30 min has been shown to negatively affect subsequent endurance performance [20]. The mentally fatiguing task in the present study was longer compared to the study of Pageaux et al. [20]. Second, the fixed workload part of 45 min could have counteracted the negative effect of mild mental fatigue on performance (i.e. exercise has a restorative effect). Potentially the mild mental fatigue induced in the present study could affect endurance performance in longer duration or open-loop tests. Another possibility could be that, as suggested by the study of Martin et al. [34], endurance trained athletes are more resistant to the negative effects of mild mental fatigue on subsequent endurance performance. The population tested in the present study was slightly better trained [i.e. performance level 3 according to De Pauw et al. [21]] compared to the populations (i.e. performance level 2) used in other studies that did find a negative effect of mental fatigue on endurance performance [2, 20]. Therefore the better training status of our participants may explain, in part, the lack of an effect of mild mental fatigue on endurance performance [34]. A last and possibly the most reasonable explanation is that mild mental fatigue does not further reduce endurance performance when the brain is already stressed by a hot environment. Consequently we speculate that a floor effect was observed in the present study. Meaning that if one stresses the brain (e.g. heat stress, mental fatigue, …) endurance performance will decrease, at some point however further stressing the brain (e.g. combining heat stress and mental fatigue) will not result in a further reduction of performance and a floor effect is observed. This emphasizes the importance of the brain in endurance performance and might indicate that it is irrelevant which stressor (heat and the increased physiological strain or mental fatigue) leads towards a higher perception of effort; relevant is whether or not the stressor increases perception of effort (see the psychobiological model [35, 36]). The higher perception of effort experienced during endurance exercise in a hot environment or when mentally fatigued may share a common psychobiological mechanisms: negative valence. Exercising in the heat is associated with thermal discomfort whilst mental fatigue is known to induce a more negative mood. The valence of emotional stimuli have been shown to affect perception of effort [37] and the activity of the cingulate cortex [38], prefrontal and premotor cortical areas [39] related to perception of effort [40, 41]. So it is plausible that a similar psychobiological mechanism may explain the effects of heat stress and mental fatigue on perception of effort and why the effects of the two stressors do not summate. In other words, in conditions of thermal discomfort, the negative effects of mild mental fatigue on mood may not lead to further increase in negative valence and perception of effort. EEG data support this hypothesis; Nybo & Nielsen [14] observed that perception of effort during prolonged exercise in hot environments is associated with changes in cerebral electrical activity rather than changes in the electromyogram of the exercising muscles. They reported a higher α/β-activity ratio in the heat, mainly due to a ~50% lower β-activity in the heat [14]. Mental fatigue has been repeatedly associated with elevated frontal θ and frontal, central and parietal α-power [6, 42], an association that also is supported by the results in the present study. Consequently mental fatigue might also increase perception of effort via the same mechanism proposed by Nybo & Nielsen [14], raising α/β-activity ratio during an endurance task. This makes a floor effect neurobiologically plausible.

3.1.6 Conclusion

The subjective workload scale and the higher salivary cortisol levels after the Stroop task substantiated perceptually and biologically that the Stroop task was more mentally demanding and stressful than the control task. The demanding nature of the Stroop task eventually caused increases in θ-, $\alpha 1$-, $\alpha 2$-activity and P3b-latency and a decrease in P3b-amplitude. These results and the higher M-VAS support that at least a ‘mild form’ of mental fatigue was induced. The mild mental fatigue did however not influence participants’ psychological or physiological responses during the endurance task, nor their performance. Possible explanations are: 1) the mild form of mental fatigue was insufficient to alter performance on a subsequent endurance task or 2) endurance trained athletes are resistant to the negative effects of mild mental fatigue on subsequent endurance performance or 3) mild mental fatigue does not reduce endurance performance when the brain is already stressed by a relatively hot environment (30 °C).

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The authors declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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Conflict of interest

The results of the present study do not constitute endorsement by ACSM. No conflict of interest is declared by the authors.

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Chapter 3: Mental fatigue and the heat-induced decrease in endurance performance

Part 2: *The role of perceptual responses in the heat-induced decrease in endurance performance*

Subjective thermal strain impairs endurance performance in a temperate environment

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3.2.1 Abstract

Purpose: The aim of this study was to test the hypothesis that subjective thermal strain can reduce endurance performance independently from the general physiological strain normally associated with impaired endurance performance in the heat. **Methods:** In 20°C and 44% relative humidity, 12 endurance-trained athletes (1♀ 11♂; mean ± SD; age:27 ± 6 y; VO_2max:61 ± 6 ml/kg/min) performed a time to exhaustion (TTE) test in two different experimental conditions: with an electric heat pad applied to the subjects' upper back (HP) and control (CON: without heat pad). In both conditions, subjects cycled to volitional exhaustion at 70% of their VO_2max. Cardiorespiratory, metabolic, thermoregulatory and perceptual responses were measured throughout the TTE test and compared at 0%, 50% and 100% isotime and at exhaustion. **Results:** TTE was reduced by 9% in HP (2092 ± 305s) compared to CON (2292 ± 344s; p=0.023). The main effect of condition on thermal discomfort at isotime (p=0.002), the effect of condition on thermal sensation at 0%-isotime (p=0.004) and the condition by isotime interaction on rating of perceived exertion (p=0.036) indicated higher subjective thermal strain in HP compared to CON. None of the measured cardiorespiratory, metabolic and thermoregulatory variables differed significantly between conditions. **Conclusion:** Our novel experimental manipulation (HP) was able to induce significant subjective thermal strain and reduce endurance performance in a temperate environment without inducing the general physiological strain normally associated with impaired endurance performance in the heat. These results suggest that subjective thermal strain is an important and independent mediator of the heat-induced impairment in endurance performance.

Key words: Time to exhaustion: Local heat; Thermal discomfort; Thermal sensation; Perception of effort

3.2.2 Introduction

Endurance performance during whole-body exercise (e.g. running, cycling, and rowing) is known to be impaired in the heat [1-3]. The aetiology of this impairment is multifaceted and physiologically encompasses a higher cardiovascular strain, a decrease in maximal aerobic capacity , a higher internal body temperature (Tcore), hypohydration, neuromuscular changes within the central nervous system and an altered metabolism in the active muscles [4]. A review by Nybo et al. [4] provides a clear overview on the general physiological strain normally associated with impaired endurance performance in the heat.

In addition to physiological strain, performing endurance exercise in the heat is associated with significant subjective thermal strain [4]. This strain is indicated by ratings of heat sensation, thermal discomfort and higher perceived exertion. It is generally accepted that subjective thermal strain plays a role in the deterioration of endurance performance observed in the heat [4-7]. Nonetheless, the exact extent to which it causes this deterioration is unknown as it is difficult to dissociate subjective thermal strain from the general physiological strain normally associated with impaired endurance performance in the heat (e.g. increased Tcore and decreased stroke volume, SV).

A line of research that provides some insight on the role of subjective thermal strain in the heat-induced impairment in endurance performance is the research on the effects of cooling interventions. Research on the effects of cooling interventions on endurance performance is available in abundance [6, 8-10]. Cooling vests, collars, sprays/gels/solutions are some of the interventions that have been explored and often found to reduce subjective thermal strain and improve endurance performance. Most of these studies, however, have not controlled for the physiological changes associated with endurance exercise in the heat, as the main aim was often to assess whether the intervention improves endurance performance, rather than to dissociate subjective thermal strain from physiological strain [8, 9]. For example Kenny et al. [8] observed that wearing an ice cooling vest during walking under uncompensable heat stress lowered Tcore and HR responses as well as ratings of heat sensation and perceived exertion and that this led to an increased time to exhaustion (TTE). Cuttell et al. [11] also found an improved cycling TTE in the heat when wearing an ice cooling vest and attributed this mainly to the improved heat sensation, however the ice cooling vest also consistently decreased HR during the TTE test. Nonetheless, some of the research on cooling interventions succeeded in dissociating subjective thermal strain from the physiological strain that is traditionally associated with the heat-induced impairment in endurance performance. Tyler and Sunderland [12] reported a reduced heat sensation by applying a cooling collar during the entire timespan of a TTE test in the heat (~32°C) without affecting the physiological strain at any isotime point during the TTE test. The result was an improvement in TTE of 13.5% [12]. Flood et al. [13] observed that serial L-menthol mouth rinsing extended exercise time in the heat at a fixed RPE (i.e. 16) by 7%, without affecting Tcore, Tskin, body mass loss, oxygen uptake (VO2), minute ventilation (VE), HR or thermal discomfort. Serial L-menthol mouth rinsing only decreased heat sensation. The results of the studies of Tyler and Sunderland [12] and Flood et al. [13] demonstrate that subjective thermal strain may play a role in the heat-induced reduction in endurance performance, independently from the heat-induced physiological strain.

Besides a lack of studies that explicitly attempted to evaluate the independent role of subjective thermal strain in the heat-induced reduction in endurance performance, subjective thermal strain has been almost exclusively investigated with interventions that reduce it during endurance exercise (i.e. cooling interventions). This is possibly due to the difficulty in increasing subjective thermal strain without increasing the ambient temperature. Only Schlader et al. [6] and Lee et al. [14] made an attempt to negatively affect subjective thermal strain during exercise. Lee et al. [14] succeeded to increase heat sensation by serially feeding 50°C drinks during a 90-min low-intensity cycling task, however, it also increased HR. In addition, they found no difference in performance in the subsequent TTE test [14]. Schlader et al. [6] applied capsaicin cream (i.e. a substance that increased heat sensation and thermal discomfort independent of changes in local (skin) temperature, but probably did affect local skin blood flow [15]) to the face of the subjects prior to a fixed RPE 16 cycling task in a temperate condition. Schlader et al. [6] did however not find any decrease in performance compared to a control condition. It was hypothesized that this could be due to capsaicin likely eliciting thermal pain, but not necessarily thermal discomfort [6]. Therefore it was suggested that, given the nociceptive nature of capsaicin, Schlader et al. [6] simply were not able to adequately test their hypotheses.

The purpose of the present study was to further test the hypothesis that subjective thermal strain can reduce endurance performance independently from the general physiological strain normally associated with impaired endurance performance in the heat (e.g. increased Tcore and decreased SV). This hypothesis was tested by aggravating heat sensation and thermal discomfort (rather than ameliorating them) by locally applying an electric heat pad on the upper back during endurance exercise in a temperate environment. Endurance performance was measured using a TTE test on a cycle ergometer at 70% VO_2max in a group of endurance-trained subjects. This TTE test has been shown to be sensitive to changes in endurance performance due to a warm ambient temperature (30°C ←→ 10°C) with TTE dropping by 36% in a study of Galloway and Maughan [16]. We hypothesized that the sensation of heat and the thermal discomfort induced by the heat pad would be associated with a higher perception of effort and premature exhaustion despite no negative effects of the heat pad on the cardiorespiratory, metabolic and thermoregulatory responses to endurance exercise in a temperate environment.

3.2.3 Methods

3.2.3.1 Subjects and ethical approval

Fourteen trained cyclists or triathletes, of which two participants dropped out (due to sickness and incompatible training schedule), volunteered to participate in the present study. Eventually twelve trained cyclists or triathletes (1♀ 11♂; mean ± SD; age: 27 ± 6 y, height: 177.0 ± 7.9 cm, body mass: 69.8 ± 9.8 kg, VO_2max: 61 ± 6 ml/kg/min, peak power output (Wpeak): 399 ± 54 W) were included in this study. None of the subjects had any known mental or somatic disorder. Subjects were also non acclimatized to heat (thus also not to the subjective experience of performing in the heat). Our subjects can be included in performance level 3 in the classification of subject groups in sports science research [17, 18]. Each subject gave written informed consent prior to the study. Experimental protocol and procedures were approved by the local ethics committee. All subjects were given written instructions describing all procedures related to the study but were naive of its main aims and hypotheses. In other words, individuals were unaware that we strove towards creating a higher subjective thermal strain with the heat pad and that we expected that this increased subjective thermal strain would impair their endurance performance. Participants were informed that the purpose of the study was to investigate the influence of locally applied heat on cardiorespiratory, metabolic and thermoregulatory responses during endurance exercise.

3.2.3.2 Experimental protocol

On the first visit to the lab subjects underwent a medical examination by a physician. Subjects were excluded if they presented with any medical history, family history or medication or drug use that would prevent them from safely completing the experiment. Subjects then completed an incremental exercise test to determine their VO_2max (MetaLyzer 3B, Cortex Biophysik, Leipzig, Germany). This incremental exercise test was conducted on a cycle ergometer (Lode Excalibur Sport, Groningen, the Netherlands) in order to determine VO_2max similarly to the protocol used by Galloway and Maughan [16]: the test started at 50 W for 1 min, thereafter the resistance was increased by 25 W each min until exhaustion [operationally defined as a pedal frequency of less than 60 revolutions/min (RPM) for more than 5 s despite strong verbal encouragement]. The 40% (24 ± 3 ml/kg/min) and 70% (43 ± 4 ml/kg/min) VO_2max was calculated and the associated wattage [134 ± 22 W; 261 ± 42 W (=65 ± 4 % of peak power output) respectively] selected. Before the incremental exercise test the position on the cycle ergometer was adjusted for each subject, and settings were recorded and reproduced at each subsequent visit. Subjects were also given standard instructions for overall rating of perceived exertion (RPE) using the 15-point scale (6-20) developed by Borg [19]. In order to acquaint participants with the feelings of exertion that should be rated 7, they were asked to cycle unloaded at 50 rpm for 3 min before the start of the incremental exercise test. To establish the high anchor point participants were asked to assign a rating of 19 to the conscious sensation of how hard, heavy, and strenuous exercise felt at the end of the incremental exercise test.

The subjects were asked to report to the lab for 3 consecutive testing sessions at the same time of day (i.e. within-participants trials were performed at the same time of day), which were separated by at least 3 days to ensure full recovery. The first testing session was a familiarization session (to get to know the routine, the equipment and to avoid learning effects), followed by an intervention session (with heat pad; HP) and a control session (without heat pad; CON) in a randomized and quasi counterbalanced (due to 2 drop outs: 7 participants performed first CON, 5 performed first HP) order (www.randomization.com). All testing sessions were conducted in 20 ± 0.3 °C and in a relative air humidity of 44 ± 3.5 %. Preceding the beginning of the TTE test, the subjects' body mass was measured wearing only cycling shorts and a mood and motivation questionnaire (see *Psychological measurements* section) was filled in. After completion of the questionnaires (~3min), the heat pad (see *Heat pad* section) as well as all physiological measurement instruments were applied, and blood glucose was assessed (see *Physiological measurements* section). Subsequently the TTE test was started (see *Time to exhaustion test*). Physiological and perceptual responses were measured throughout the TTE test (at 5-min intervals and at minute 1; see *Physiological and Psychological measurements section*). Immediately after completing the TTE test, all physiological variables were measured (see *Physiological and Psychological measurements* for details) and subjects were asked to fill in the same mood-questionnaire as in the beginning of the protocol (see *Psychological measurements*). All subjects were given written instructions to drink 35 ml of water per kilogram of body mass in the 24 h before each visit, sleep for at least 7 h, refrain from the consumption of alcohol and avoid any vigorous exercise 24 h before each visit. Also the use of caffeine 3 h before each visit was prohibited. Finally, subjects were instructed, depending on the hour their session took place, to consume 200 ml of orange juice (Capri-Sun orange, 352 kJ) and a cereal bar (Asda, 555 kJ) two hours prior the beginning of the TTE test if their session took place in the morning; if their session took place in the afternoon subjects were asked to record their fluid and food intake during the day of the familiarization session and to replicate this the following two sessions. At each visit to the lab, subjects were asked to complete a pretest checklist to ascertain that they had complied with the instructions. Participants were also asked to declare if they had taken any medication/drug or had any acute illness, injury, or infection.

Time to exhaustion test

Despite the tendency nowadays to prefer time trials to measure endurance performance in sports science due to lower variability and more ecological validity, a TTE test was chosen in the present study in order to control for physiological changes induced by differences in power output (e.g. increased metabolic heat production). Moreover, TTE tests have been shown to have an adequate sensitivity to quantify changes in endurance performance and the effects of arterial oxygenation and presumably other factors affecting endurance performance [20]. The TTE test consisted of a 5-min warm-up (WU) at 40% of VO_2max followed by a rectangular workload corresponding to the wattage analogue with 70% VO_2max. Pedal frequency was freely chosen between 70 and 120 RPM. Time to exhaustion was measured from the start of the rectangular workload until the pedal frequency became less than 70 RPM for more than 20 s. To promote a similar motivation towards the TTE test in each condition, a £100-Amazon voucher was offered for the best overall endurance performance (= the best total time over both TTE tests: one in HP and in CON). During the TTE test, subjects were not informed regarding time lapsed, also no feedback was provided regarding power output, HR or any other cardiovascular, respiratory or thermoregulatory measure and no verbal encouragement was given. Subjects were only alerted when they dropped below 70 RPM. Once alerted they had 20 s to increase RPM above 70 or the TTE test was terminated. Every 15 min subjects were required to drink 2 ml/kg of body mass of water kept at room temperature in 1 min (via a straw so that the oro-(mouth) mask could stay in position [21]).

Heat pad

In both conditions participants wore a specifically designed t-shirt with a pocket for the heat pad, but only in HP the 40 x 30 cm electric heat pad (Beurer - heating pad - HK 35; CE-certified) was inserted in the pocket and turned on at a heat level 3 equivalent to a pad temperature of ~40 °C. This intervention was chosen based on pilot data suggesting its ability to induce subjective thermal strain without inducing the physiological strain normally associated with endurance exercise in the heat (e.g. increased Tcore and decreased SV). The heat pad covered zones 13 and 14 (upper medial back and both scapulae) described in the study of Gerrett et al. [22]. This specific localization of the heat pad was chosen based on thermal sensitivity to warmth [22]. The participants had time (~10 min) to acclimatize to the heat pad applied to their back and to the ambient temperature in the climate chamber during the instrumentation of the equipment to measure all physiological variables.

Physiological measurements

Blood glucose concentration (mg/dl; ACCU-CHECK Aviva Blood Glucose Meter System, Roche Diagnostics, Mannheim, Germany) and body mass were assessed before and after the TTE test. Blood glucose was assessed in a 0.6-µl sample of whole blood from the tip of the right index finger. Body mass loss, taking into account the water intake during the TTE, was calculated in kg and divided by the TTE test in hours in order to calculate sweat rate. Blood lactate concentration ([Bla]), Tcore, Tskin, HR, SV, cardiac output (CO), VO_2 and VE were measured throughout the TTE test at fixed 5-min intervals and additionally at minute 1 and at exhaustion. [Bla] (mmol/l) was assessed in a 5-µl sample of whole blood taken from the right earlobe (determined enzymatically; EKF; BIOSEN 5030, Magdeburg, Germany). To monitor Tcore subjects inserted a rectal thermistor 10 cm beyond the anal sphincter (Gram Corporation LT-8A, Saitama, Japan), and skin temperature probes (Gram Corporation LT-8A, Saitama, Japan) were attached to four sites (chest, upper arm, thigh, and calf) to monitor Tskin. Mean weighted skin temperature was measured according to the method described by Ramanathan [23]. A transthoracic bioimpedance device (Physioflow PF05L1, Manatec, Petit-Ebersviller, France) was used to measure HR, stroke volume (SV) and CO during exercise. Two sets of two electrodes (Ambu Blue Sensor VL, Ambu A/S, Ballerup, Denmark), one transmitting and the other one receiving a low amperage alternating electrical current, were applied on the supraclavicular fossa at the left base of the neck and along the xiphoid. Another set of two electrodes was used to monitor a single ECG lead in the V1/V6 position. All electrode placement areas were shaved if necessary, cleaned with an alcohol pad, and dried with a paper towel. All procedures and calculation of SV and CO were according to the methods described in the study of Marcora et al. [24]. These data were averaged over 1-min periods before statistical analysis. VO_2 (ml/min/kg) and VE (l/min) during exercise were measured breath-by-breath using a computerized metabolic gas analysis system (MetaLyzer 3B, Cortex Biophysik, Leipzig, Germany) connected to an oro-(mouth) mask (7600 series, Hans Rudolph, Kansas City, MO). This automated device was calibrated before each test using certified gases of known concentration (11.5% O2 and 5.1% CO2) and a 3.0-liter calibration syringe (series 5530, Hans Rudolph). All respiratory gas exchange data were averaged over 1-min periods before statistical analysis.

Psychological measurements

The Brunel Mood Scale (BRUMS) developed by Terry et al. [25] was used to assess mood before and after the TTE test. This questionnaire, which is based on the Profile of Mood States, contains 24 items (e.g. angry, uncertain, miserable, tired, nervous, energetic) divided into six respective subscales: anger, confusion, depression, fatigue, tension, and vigor. The items were answered on a 5-point Likert scale (0 = not at all, 1 = a little, 2 = moderately, 3 = quite a bit, 4 = extremely), and each subscale, with four relevant items, can achieve a raw score in the range of 0 to 16. The BRUMS has been widely used to measure mood in athletes and changes in mood in response to both physical and mental exertion [25, 26]. Motivation related to the TTE test was measured using the success motivation and intrinsic motivation scales developed and validated by Matthews et al. [27]. This scale has been used previously to measure task-related motivation in exercise studies [24, 28, 29] and it is sensitive to motivational changes induced by a monetary reward [30]. Each scale consists of 7 items (e.g. “I want to succeed on the task” and “I am concerned about not doing as well as I can”) scored on a 5-point Likert scale (0 = not at all, 1 = a little bit, 2 = somewhat, 3 = very much, 4 = extremely). Therefore, total scores for these motivation scales range between 0 and 28. Ratings of perceived exertion, thermal discomfort (Tdcomf) and thermal sensation (Tsens) were obtained from the subject during the final 15 s of the first minute, of each 5 min of exercise and at exhaustion. Perception of effort was rated using the Borg RPE scale displayed in front of the subject throughout the TTE test. Participants were asked to rate how heavy and strenuous the exercise feels, the RPE scale ranges from 6 (no exertion at all) through 13 (somewhat hard) to 20 (maximal exertion). The scales to asses Tdcomf and Tsens were the ones used in the study of Filingeri et al. [31]. A 13-point thermal sensation scale (i.e. −6, very cold; −4, cold; −2, slightly cool; 0, neutral; +2, slightly warm; +4, hot; +6, very hot) and a 13-point thermal comfort scale (i.e. −6, very uncomfortable; −4, uncomfortable; −2, slightly uncomfortable; 0, neutral; +2, slightly comfortable; +4, comfortable; +6, very comfortable) were used [31]. No descriptors were applied to intermediate scores (i.e. −5; −3; −1; +1; +3; +5). The participants familiarized with the scales during the familiarization.

3.2.3.3 Statistical analysis

All data are presented as means ± standard error (SE) unless stated otherwise. The Shapiro-Wilk test was used to test the normality of the data. Sphericity was verified by the Mauchly's test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted with the Greenhouse-Geisser procedure.

Wilcoxon Signed Ranks Tests were used to assess the effect of condition (HP vs CON) on TTE, and on each subscale of the BRUMS pre and post the TTE test.

Paired t-tests (2-tailed) were used to assess the effect of condition (HP vs CON) on motivation, body mass loss, sweat rate and on the physiological ([Bla], Tcore, Tskin, SV, VO2 and VE) measures at exhaustion. Non-normally distributed physiological (HR, SV and CO) and perceptual (Tsens, Tdcomf and RPE) measures at exhaustion were analysed with a Wilcoxon Signed Ranks Test.

A 2 x 2 (Condition x Time) fully repeated measures ANOVA was used to assess the effect of condition on glucose.

A 2 x 3 (Condition x Isotime) fully repeated measures ANOVA was used to assess the effect of condition on the continuously measured physiological ([Bla], Tcore, Tskin, HR, CO and VO_2) and perceptual (Tdcomf and RPE) measures at 0% (60 ± 0 s), 50% (1050 ± 154 s) and 100% (1925 ± 306 s) of isotime during the TTE test. In non-normally distributed physiological (VE and SV) and perceptual (Tsens) measures the effect of condition in each isotime interval was analysed with a Wilcoxon Signed Ranks Test. To assess the effect of isotime (0%, 50% and 100%) on these measures, Friedman tests were used. To obtain these isotime data, the value of each parameter at 100% isotime was established by identifying the shortest TTE test accomplished by each individual over their two tests. The value for each variable attained during the final full 5 minutes of the shortest TTE test were then compared to the value attained during the equivalent minute of the longer TTE test. The minute identified as 100% isotime was subsequently different from the point of exhaustion (i.e. all physiological and perceptual measures were taken one last time at exhaustion). This minute identified as 100% isotime (1925 ± 306 s) was multiplied by 0.5 and rounded to the nearest time of rating where necessary to attain the value corresponding to 50% isotime (1050 ± 154 s). Isotime values for 0% (60 ± 0 s) were attained by comparing values for the first full minute of each TTE test.

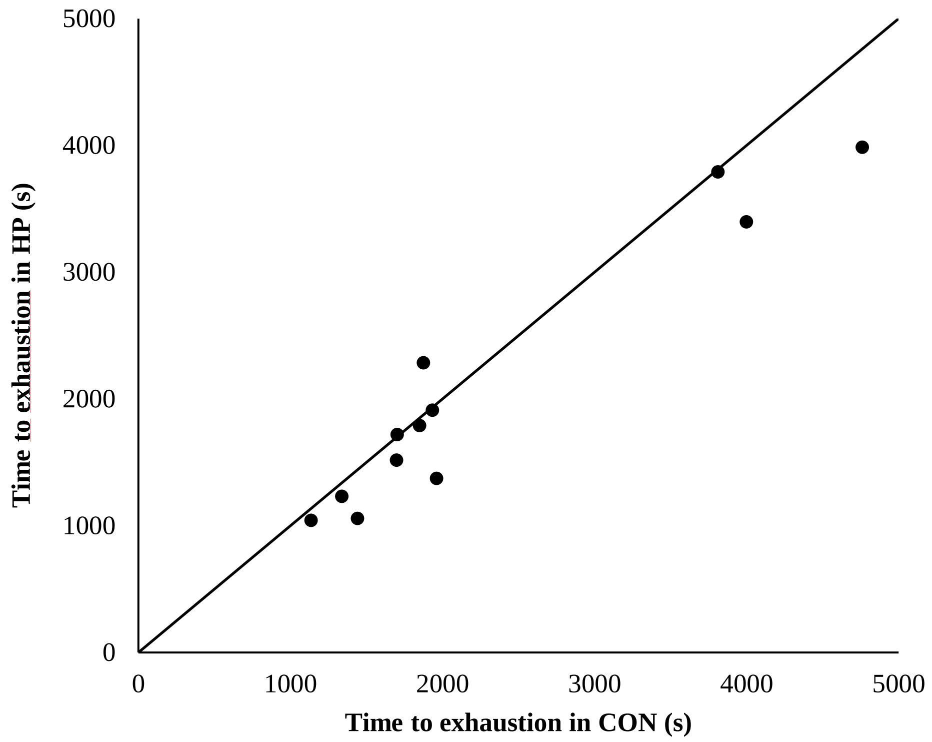
If a significant interaction effect (Condition x Isotime) in the fully repeated measures ANOVAs was observed, paired t-tests were performed in order to interpret the effect of the heat pad in each time interval and one-way repeated measures ANOVAs were performed in order to interpret the effect of isotime in each condition. If no significant interaction effect in the fully repeated-measures ANOVAs was observed, the main effect of the heat pad and isotime was immediately interpreted. Significance was set at 0.05 for all analyses, which were conducted using the Statistical Package for the Social Sciences, version 22 (SPSS Inc., Chicago, IL, USA).

3.2.4 Results

3.2.4.1 Endurance performance

TTE was significantly lower in HP (2092 ± 305 s) compared with CON (2292 ± 344 s; p=0.023). Individual TTE was lower in HP compared to CON in 10 of 12 subjects (Fig. 1).

Fig. 1 Effect of heat pad on time to exhaustion (TTE; n = 12). Scatterplot of TTE in HP (heat pad condition) and TTE in CON (control condition). The points below the identity line represent a decreased endurance performance in HP compared with CON in individual participants.



3.2.4.2 Psychological measures

Subjective thermal strain

Tsens was significantly higher in HP (2.8 ± 0.3) compared to CON (1.4 ± 0.3) at 0% isotime (p=0.004), while at 50% (p=0.088) and 100% (p=0.167) isotime no difference between conditions was observed (Fig. 2). In addition subjects rated Tdcomf consistently higher in HP during the TTE test at all isotimes (HP: -3.6 ± 0.3; CON: -2.4 ± 0.4; F(1,11)=15.4; p=0.002; partial η^2=0.58; Fig. 3). For RPE an interaction between condition and isotime was observed (F(2,22)=3.9; p=0.036; partial η^2=0.26). Visual inspection of this significant interaction effect suggests a quicker increase in RPE in the latter stages of the TTE test in the HP condition compared to CON (Fig. 4). However, follow-up tests did not demonstrate any significant difference between conditions at any isotime point (all p≥0.132). Regarding the effect of isotime, all perceptual variables (Tsens, Tdcomf and RPE) changed significantly over time during the TTE test (p<0.001; see Fig. 2, 3 & 4). At exhaustion, neither Tdcomf (p=0.104) nor RPE (p=0.358) were significantly different between conditions (Fig. 3 & 4). Only Tsens was significantly higher in HP (5.3 ± 0.3) than in CON (4.5 ± 0.4) at the point of exhaustion (p=0.031, Fig. 2).

Fig. 2 Effect of heat pad on thermal sensation during the time to exhaustion (TTE) test. # Significant main effect of time ($p < 0.05$). * Significant effect of condition ($p < 0.05$). Data are presented as means ± standard error. Minute 0 represents start of TTE test. HP heat pad condition, CON control condition.

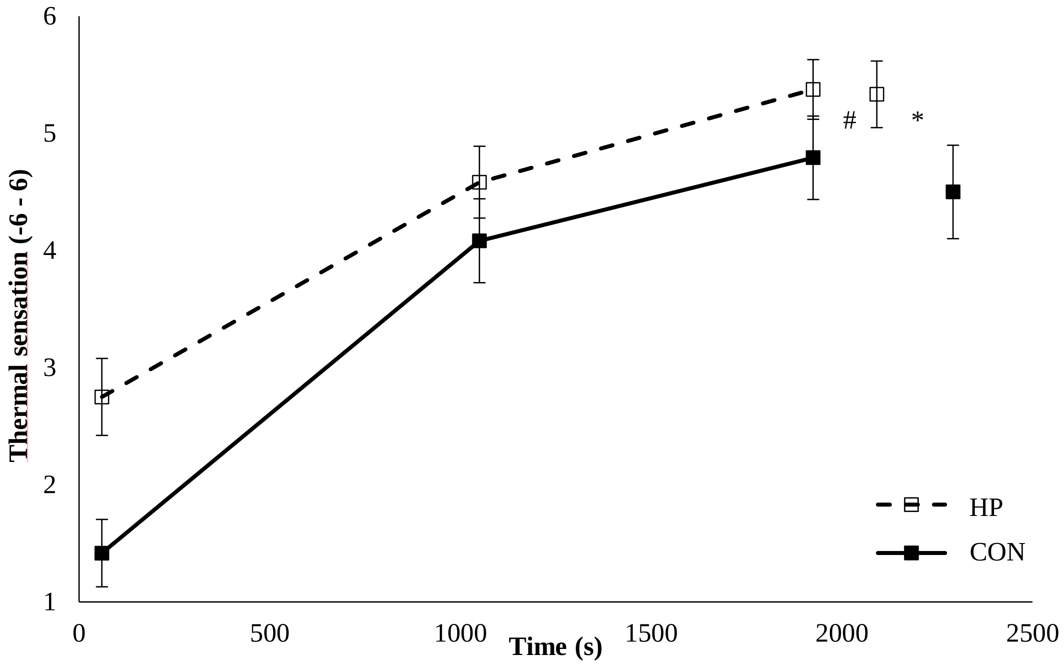


Fig. 3 Effect of heat pad on thermal discomfort during the time to exhaustion (TTE) test. # Significant main effect of time ($p < 0.05$). † Significant main effect of condition ($p < 0.05$). Data are presented as means ± standard error. Minute 0 represents start of TTE test. HP heat pad condition, CON control condition.

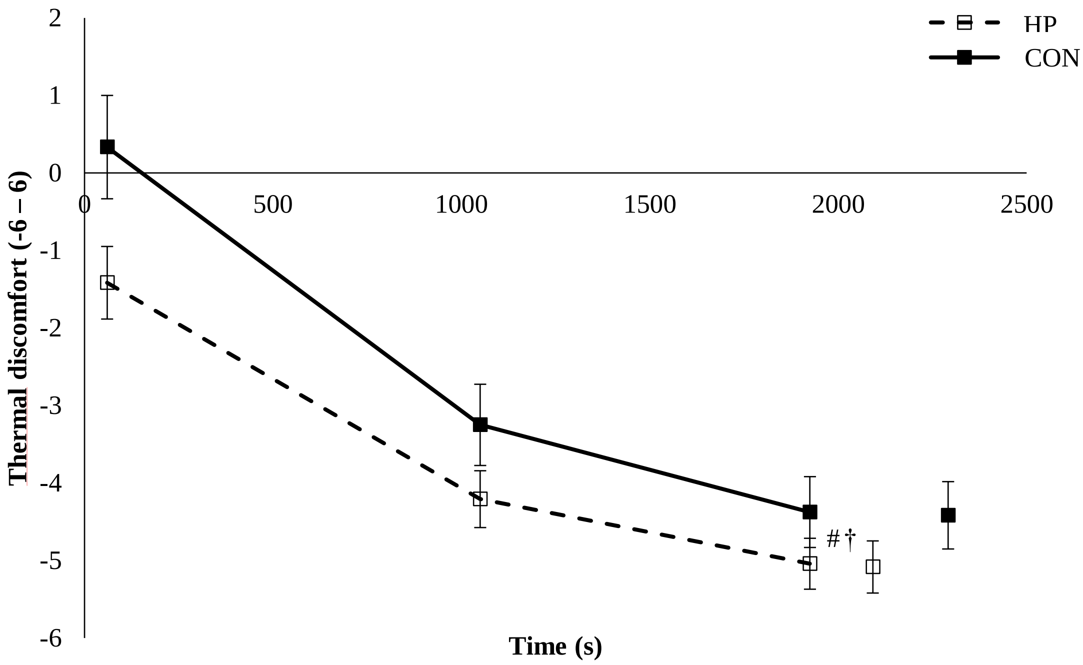
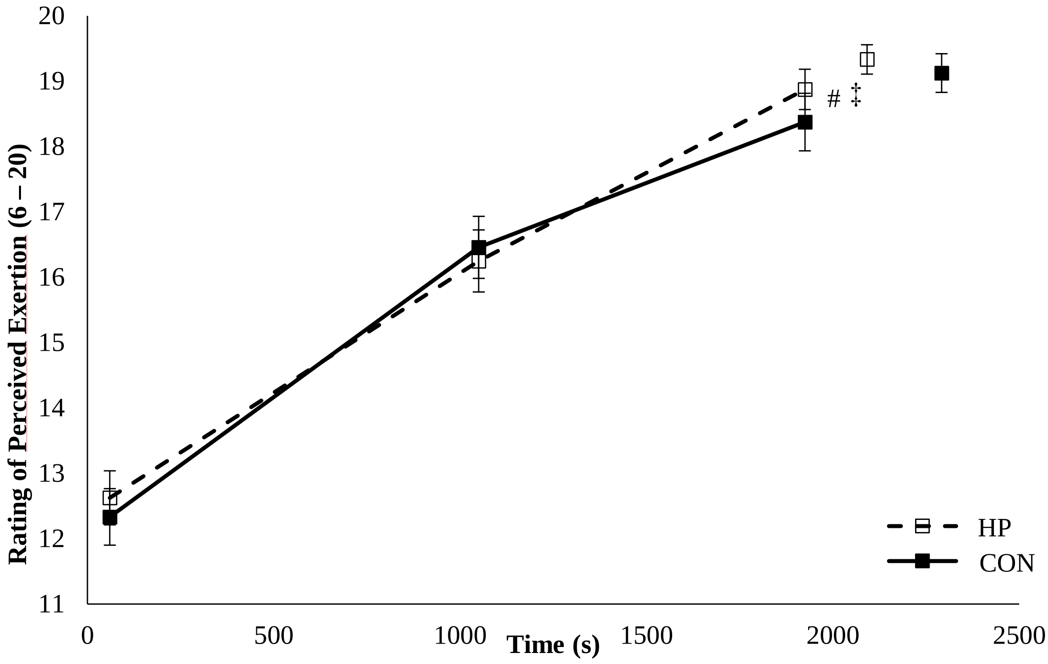


Fig. 4 Effect of heat pad on rating of perceived exertion during the time to exhaustion (TTE) test. # Significant main effect of time ($p < 0.05$). ‡ Significant interaction effect between condition and time ($p < 0.05$). Data are presented as means ± standard error. Minute 0 represents start of TTE test. HP heat pad condition, CON control condition.



Motivation and mood

No significant differences in success (p=0.870) or intrinsic motivation (p=0.111) regarding the TTE test were observed between conditions. The fatigue-subscale of the BRUMS indicated participants experienced the TTE test as fatiguing in both conditions (p≤0.005). No effects of condition or time were found for mood in any other subscale of the BRUMS measured pre and post the TTE test (p≥0.107).

3.2.4.3 Physiological measures

At isotime, all physiological variables ([Bla], Tcore, Tskin, HR, SV, CO, VO_2 and VE) changed significantly over time (all main effects of time, p<0.017; see Table 1), but none of them (including the non-normally distributed SV and VE variables) was significantly affected by the heat pad (p≥0.219; Table 1). At exhaustion, none of the physiological variables were affected by the heat pad (p≥0.284; Table 1), only for [Bla] a trend towards a significantly higher concentration in CON was observed (t(11)=-2.2; p=0.051). Body mass loss due to the TTE test (p=0.795; HP: 0.878 ± 0.171 kg; CON: 0.850 ± 0.159 kg) and sweat rate (p=0.189; HP: 1.66 ± 0.29 l/hr; CON: 1.35 ± 0.16 l/hr) did not differ between conditions, and also the glucose concentration did not differ between conditions (p=0.682) nor in time (p=0.188).

Table 1. Physiological responses during the time to exhaustion test at all isotimes (0%, 50% and 100%) and exhaustion in HP and CON (Mean ± SE).

Physiological measure		**0% (60 ± 0s)**	**50% (1050 ± 154 s)**	**100% (1925 ± 306 s)**	**Exhaustion**
HR (beats/min) #	HP	138 ± 4	172 ± 3	181 ± 2	182 ± 3
	CON	137 ± 4	168 ± 4	180 ± 2	181 ± 2
SV (ml) #	HP	119 ± 7	144 ± 9	141 ± 7	146 ± 8
	CON	129 ± 11	152 ± 11	141 ± 8	144 ± 7
CO (l/min) #	HP	16.5 ± 1.1	24.5 ± 1.3	25.3 ± 1.0	26.4 ± 1.4
	CON	17.7 ± 1.4	25.4 ± 1.6	25.3 ± 1.2	26.0 ± 1.1
VO_2 (l/min) #	HP	2.4 ± 0.1	3.5 ± 0.2	3.7 ± 0.2	3.5 ± 0.2
	CON	2.4 ± 0.1	3.7 ± 0.2	3.6 ± 0.2	3.6 ± 0.2
VE (l/min) #	HP	56.2 ± 2.5	99.2 ± 4.8	109.6 ± 6.5	113.7 ± 7.4
	CON	56.9 ± 2.2	98.5 ± 4.5	105.3 ± 5.8	112.2 ± 6.3
Tcore (°C) #	HP	37.0 ± 0.2	38.1 ± 0.1	38.8 ± 0.2	39.0 ± 0.2
	CON	37.2 ± 0.1	38.0 ± 0.1	38.6 ± 0.2	38.9 ± 0.2
Tskin (°C) #	HP	31.7 ± 0.3	34.2 ± 0.2	34.4 ± 0.3	34.4 ± 0.2
	CON	31.8 ± 0.2	34.0 ± 0.3	34.2 ± 0.3	34.3 ± 0.3
Bla (mmol/l) #	HP	1.7 ± 0.2	3.9 ± 0.5	4.7 ± 0.6	5.0 ± 0.7
	CON	1.7 ± 0.2	4.2 ± 0.5	5.0 ± 0.6	5.7 ± 0.7

 # indicates a significant main effect of time ($p<0.05$); s seconds, HR heart rate, HP heat pad condition, CON control condition, SV stroke volume, CO cardiac output, VO_2 oxygen consumption, VE minute ventilation, Tcore core temperature, Tskin skin temperature, Bla blood lactate.

3.2.5 Discussion

This study aimed to test the hypothesis that subjective thermal strain is an important determinant of endurance performance, rather than just an epiphenomenon of the physiological strain normally associated with the endurance exercise impairment in the heat. This hypothesis was tested by aggravating heat sensation and thermal discomfort rather than ameliorating them. This effect was achieved by locally applying a heat pad to the upper back of endurance-trained subjects performing a TTE test on a cycle ergometer in temperate conditions. This novel experimental manipulation was successful in inducing higher ratings of heat sensation and thermal discomfort, and a quicker increase in RPE during the TTE test compared to the control condition (no heat pad). Despite no negative effects of the heat pad application on the measured cardiorespiratory, metabolic and thermoregulatory responses to endurance exercise in a temperate environment, TTE was impaired by 9%. The size of this negative effect on TTE is comparable to the effect (-13%) of a 10°C ambient temperature difference (31°C vs 21°C, Tcore at exhaustion was respectively 40.1°C and 39.4°C) observed in the study of Galloway & Maughan [16], and substantiates that subjective thermal strain is an important mediator of the heat-induced reduction in endurance performance. As clearly shown in Fig. 1 there was a group of three participants whose TTE (3957 ± 449 s) was significantly longer than the rest (n=9; mean-TTE=1603 ± 354 s). The most likely explanation for this difference in endurance performance is that the group with the longer TTE was cycling below the anaerobic threshold (n=3; Fig. 1; mean [Bla]=2.91 ± 1.36 mmol/l) whilst the other group was cycling closer to it (n=9; Fig. 1; mean [Bla]=4.36 ± 1.44 mmol/l).

The present study is not the first study to put forward that subjective thermal strain is an important mediator of thermoregulatory behaviour [4-6] and an important determinant of endurance performance [4-6, 10]. However, the only way to provide evidence in favour of its causal role in endurance performance is to dissociate subjective thermal strain from physiological strain. Previously, this has been done by reducing subjective thermal strain in a hot environment [12, 13], but not yet by aggravating heat sensation and thermal discomfort. The present study provides further evidence that subjective thermal strain is an important determinant of endurance performance. As discussed earlier, local application of the heat pad to the upper back of the subjects did not affect the general cardiorespiratory, metabolic and thermoregulatory responses to endurance exercise in a temperate environment. Therefore, changes in [Bla], Tcore, Tskin, HR, SV, CO, VE and VO_2 cannot explain the negative effect that this experimental manipulation had on endurance performance. Although we followed up the general physiological measures, these give no indication of the locally induced changes by the heat pad. The heat pad will of course have increased the number of thermosensors that reached their activation threshold (i.e. local Tskin will have been increased). Subsequently the afferent feedback of the peripheral thermosensors located at the upper back to the central effector cells (e.g. preoptic anterior hypothalamus) will have been higher in HP compared to CON [32]. Possible thermoeffector responses in the heat are for example various aspects of thermoregulatory skin vasodilation, increased sweat rate and thermoregulatory behaviour [32]. And although some of these thermoeffector responses might have been present locally (e.g. increased local sweat rate and/or blood flow), they did not occur generally. The fact that they did not occur generally does however not exclude completely that local thermoeffector responses could have had impaired endurance performance. Specifically concerning CO, despite no difference in absolute CO was observed during the TTE test in both conditions, we can however not exclude that a redistribution of CO occurred. If present, this redistribution most logically would have resulted in a larger amount of blood flowing to the skin in the HP-condition, (1) due to the heat pad-induced vasodilation at the upper back and (2) to dissipate the added heat to the body by the local heat pad. If present, this redistribution may reduce convective oxygen delivery to the working muscles and exacerbates muscle fatigue [33]. However, the lack of a difference in [Bla] during the TTE test does not corroborate the presence of exacerbated muscle fatigue due to this potential redistribution of CO. It seems the body was physiologically able to cope with this added stress factor and no general physiological thermoeffector response was triggered by the increased afferent feedback of the peripheral thermosensors located at the upper back.

Besides physiological variables that could have possibly explained the observed reduction in TTE, multiple psychological variables could have as well. One possibility is a nocebo effect of the heat pad which may decrease motivation, self-efficacy, drive or self-esteem. To avoid as much as possible this confounding variable, we used naïve participants and informed them that the study was on the physiological effects of local heat with no suggestion of any potentially negative effect on endurance performance (see Methods). Although we did not measure all the psychological constructs potentially affected by a nocebo (see *Limitations & future suggestions*), success motivation and intrinsic motivation towards the TTE test were not found to be affected by the heat pad, and also mood before and after the TTE test did not differ between both conditions either. These psychological findings argue against a nocebo effect.

Besides triggering a nocebo-effect, the heat pad could also have worked as a distractor (i.e. diverting attention away from other task-relevant thoughts), and although such distractive strategies tend to reduce perception of effort [34] this may be at the expense of a slower-than-optimum pace during self-paced endurance tasks [35]. This explanation does however seem to be unlikely, as RPE is not decreased in HP and no pacing was demanded in the TTE test employed in the present study. Therefore, the most likely explanation for the impairment in endurance performance observed in the HP condition was the higher subjective thermal strain induced by the heat pad.

Despite the increased afferent feedback of the peripheral thermosensors located at the upper back did not trigger a general thermoeffector response, it did trigger a psychological response (i.e. increased subjective thermal strain). Among the three factors that subjective thermal strain encompasses during endurance exercise (i.e. heat sensation, thermal discomfort and perceived exertion), heat sensation was significantly different between conditions only at the beginning of the TTE test. Moreover, significantly different heat sensation levels were reached at exhaustion in both conditions, indicating that heat sensation was probably not the cardinal "exercise stopper" [36]. Thermal discomfort on the contrary was significantly worse throughout the TTE test and its levels at exhaustion did not differ significantly between conditions. This could be interpreted as evidence that people stopped exercising when they reached the highest level of thermal discomfort that they were willing (or believed to be able) to tolerate, i.e. a sensory tolerance limit [36]. However, visual inspection of the data questions this interpretation (Fig. 3). The level of thermal discomfort at exhaustion in CON (-4.4 ± 0.4) is lower than that in HP (-5.1 ± 0.3) and almost identical to the level at 50% isotime in HP (-4.2 ± 0.4). This observation suggest that participants did not stop exercising when an individual sensory tolerance limit was reached, or they should have stopped earlier in the HP condition. The most likely psychological explanation for the shorter TTE in the HP condition is the higher perception of effort induced by the heat pad. An interaction between condition and time was observed for RPE, and although follow up tests were not conclusive, visual inspection of the data suggests that RPE in HP was higher in the later stages of the TTE test compared to CON. As a result, in the HP condition, participants reached the maximum level of effort they were willing to exert (potential motivation) and decided to stop exercise earlier than in the control condition [37]. In accordance with the above outlined reasoning, Roussey et al. [38] recently stated that within the three components of subjective thermal strain, the perception of effort appears to be the key regulator of intensity when exercising in the heat while the contribution of thermal sensation/discomfort probably fluctuates according to the hyperthermia level, but also to training experience. The interpretation of our data as evidence that heat sensation and thermal discomfort did not play a role in the earlier exercise cessation in HP in the concept of a sensory tolerance limit, does however not mean that these two components of subjective thermal strain were not thought to play a role. Rather than a limit, heat sensation and especially thermal discomfort are proposed to act as determinants of endurance performance by interacting with perceived exertion (i.e. increasing the inclination rate of RPE during the later stages of the TTE), subsequently leading to the earlier termination of exercise in HP.

In the interpretation that perception of effort is the key variable in the present study, caution is warranted. The authors acknowledge that this interpretation is only supported by an interaction effect and not by significant follow-up tests. Nonetheless it is an important mechanism to consider and it gives rise to the question: 'why was perception of effort higher in HP compared to CON?'. General physiological strain did not differ between conditions and the cerebral changes associated with heat stress [39] are not plausible explanations. One possibility is that the late increase in RPE observed in the HP condition compared to CON may be due to a higher attentional focus on thermal sensation/discomfort. Excessively focusing on internal bodily sensations has already been shown to exacerbate perception of effort and negatively impact pacing and TTE [34, 40]. The observed higher subjective thermal strain in HP compared to CON does however not automatically indicate a higher attentional focus on thermal sensation/discomfort was present in HP. Participants were asked equally often in both trials to reflect on the subjective thermal strain. As such, despite no measures of attentional focus were included in the present study (see *Limitations & future suggestions*), attentional focus is hypothesized to have been similar in both HP and CON. Therefore we suggest that the late increase in RPE observed in HP might be explained by a higher activity of the premotor cortex when exercising in an unpleasant condition like when enduring very high thermal discomfort. This suggestion is supported by a neuroimaging study showing higher premotor cortex activity when unpleasant stimuli are provided during exercise [41] and increasing evidence that the activity of premotor and/or motor areas of the cortex is associated with RPE during exercise [42-44] as predicted by the corollary discharge model of perceived effort [45]. Furthermore, the continuation of exercise in the face of very high thermal discomfort most likely requires inhibitory control. This is an effortful mental process that involves many cortical areas [46] also associated with perception of effort during physical tasks [47].

Limitations & future suggestions

The authors are aware that the present study has, inevitably, its limitations. For example, the heat pad was not applied to the back in the control condition. Consequently thermal discomfort might be induced not only by the increased heat sensation of the heat pad, but also by increased pressure and sweat production on the application-site of the heat pad (i.e. upper back). Filingeri et al. [48] already pointed out that sensing temperature is not the only factor to contribute to thermoregulatory responses in humans. Perceiving cutaneous wetness is also critical. Therefore, the increased pressure and sweat production at the upper back in HP compared to CON was beneficial in order to maximize the difference in thermal discomfort between HP and CON. Subsequently the present study provides evidence that thermal discomfort can be affected by skin heat sensations/receptors without altering core temperature. In future studies, evaluating whether the heat pad-induced performance decrease is also present in self-paced endurance tasks and including specific measures of self-efficacy, self-esteem and attentional focus could provide additional valuable insights on the psychological mechanism behind the heat pad-induced decrease in endurance performance.

3.2.6 Conclusion

This study assessed the effect of a heat pad applied to the upper back on endurance performance in temperate conditions. This novel experimental manipulation was successful in inducing significant subjective thermal strain during cycling exercise and reduced the TTE of the endurance-trained subjects by 9% on average. We measured the main cardiorespiratory, metabolic and thermoregulatory parameters normally associated with heat-induced impairment in endurance performance and found that they were not significantly affected by HP. Success and intrinsic motivation and mood prior to or after the cycling task also did not differ between conditions. Therefore, the mediator of the heat pad-induced decrease in endurance performance is, most likely, the increase in subjective thermal strain and more specifically the increased thermal discomfort and its effect on perceived exertion. These results provide additional evidence that subjective thermal strain is an important determinant of endurance performance in the heat rather than an epiphenomenon and justifies the use of specific techniques aiming to reduce subjective thermal strain (e.g. menthol spray).

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The authors declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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Conflict of interests

The results of the present study do not constitute endorsement by the American College of Sports Medicine. No conflict of interest is declared by the authors.

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Chapter 4: Mental fatigue and sport-specific psychomotor performance

<u>Mental fatigue impairs visuomotor response time in badminton players and controls</u>

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4.1 Abstract

Purpose: It has recently been reported that professional road cyclists have superior inhibitory control and resistance to mental fatigue compared to recreational cyclists. We sought to assess whether badminton players also have superior executive functions and whether they are more resistant to mental fatigue than controls on a visuomotor task. **Methods:** Eleven healthy controls (mean±SD; age: 25±4y; 6 females, 5 males) and nine healthy badminton players (age: 23±3y; 4 females, 5 males) performed two experimental trials in a randomized crossover order. Participants completed a baseline visuomotor task, followed by a Flanker task. Next, they performed either a 90-min Stroop task (MF) or watched a 90-min documentary (CON). Immediately thereafter, the Flanker task and the visuomotor task were completed again. Multiple physiological and psychological measures were assessed during the protocol. **Results:** Badminton players' and controls' accuracy during the Stroop task decreased over time ($p=0.023$). Subjectively, both groups perceived the Stroop task as more mentally demanding than the documentary ($p<0.001$). In addition, higher mental fatigue was perceived in MF compared to CON, independently from group ($p=0.029$). In the visuomotor task, controls as well as badminton players reacted significantly slower on the complex stimuli when mentally fatigued (~7%; $p<0.001$). Badminton players (1109 ± 251 ms) outperformed controls (1299 ± 227 ms; $p=0.022$) in the visuomotor task. **Conclusion:** Mental fatigue negatively affects open skill-visuomotor performance in both badminton players and controls. Badminton players did not exhibit a superior executive function compared to controls.

Key words: mental exertion; response inhibition; task switching; inhibitory control; executive function

4.2 Introduction

Mental fatigue has been shown to impair multiple visuomotor related skills in sport-specific [1-4] and non-sport-specific settings [5, 6]. In addition, Smith et al. [4], Le Mansec et al. [2] and Veness et al. [3] observed that also within trained (ranging from moderately trained to elite) athletes mental fatigue has a negative effect on sport-specific visuomotor related skills. For example, Smith et al. [4] used the Loughborough Soccer Passing and Shooting Test with experienced soccer players and found that their shot speed and accuracy decreased when mentally fatigued. Similarly, Le Mansec et al. [2] found that ball speed decreased and number of faults increased in mentally fatigued table tennis players who play at regional-national level in France.

These findings are in accordance with the effect of mental fatigue on endurance performance in endurance trained athletes [7]. Based on these results, one would conclude trained/elite athletes are not immune to mental fatigue-induced impairments in sport performance. However, given the cross-over nature of all these studies, we should be careful in drawing conclusions. Trained/elite athletes might still be more resistant to mental fatigue than untrained individuals. In literature it has already been suggested that genetic and/or environmental (i.e. training effects) factors could underlie an athlete's greater resistance to mental fatigue-associated physical performance impairments [8]. Evaluating whether athletic status mediates the resistance to mental fatigue is of importance. On the one hand, it allows to determine the factors that may contribute to successful sport performance, while on the other hand it provides further insights in the mechanisms behind the detrimental effect of mental fatigue on sport performance.

In endurance sport, Martin et al. [8] was the first to design a study to specifically assess whether level of training had any influence on the effect of mental fatigue. Interestingly, they found that professional cyclists exhibited superior performance during a 30-min Stroop task compared to recreational cyclists, which is indicative of stronger inhibitory control. Moreover, professional cyclists displayed a greater resistance to the negative effects of mental fatigue on a 20-min cycling time trial than recreational cyclists [8]. Following on this first study, Clark et al. [9] also attempted to determine whether athletic status influences the effect of mental fatigue on cycling performance. Clark et al. [9] found that a 6-min cycling time trial performance in both untrained men and non-professional highly trained individuals with a history of competition in a variety of sports was unaffected by mental fatigue. Unfortunately, as in the study of Martin et al. [8], also in this study a 30-min prolonged cognitive task was employed to induce mental fatigue. Clark et al. [9] were not able to observe any decline in performance during the prolonged cognitive task, or an increase in subjective mental fatigue post the cognitive task. In addition, also the mental fatigue-associated drop in frontal cortex oxygenation (i.e. a drop in $\Delta[HbO_2]$ [10, 11]) was not observed. As such, Clark and colleagues themselves express their uncertainty whether they were successful in inducing mental fatigue in the first place [9], a limitation that is also put forward in the study of Martin et al. [8], and that might be caused by the relatively short period of increased mental load.

To directly assess whether open skill-athletes (i.e. required to react in a dynamically changing, unpredictable and externally-paced environment) might, like cyclists, be more resistant to mental fatigue than untrained individuals (i.e. controls), the effect of a 90-min mentally fatiguing task on an open skill-visuomotor task (visuomotor task; i.e. a test where a lunge movement combined with an arm extension is required) was examined in both badminton players and controls. Several studies demonstrated that sport-specific visuomotor related skills are impaired in trained athletes when mentally fatigued [2-4]. However, based on the genetic and/or environmental factors that are put forward by Martin et al. [8] as possible mediators of the mental fatigue-associated decrease in physical performance, it is still plausible visuomotor performance in trained athletes is less affected by mental fatigue. We hypothesized that mental fatigue would negatively affect performance on the visuomotor task in controls, while badminton players would demonstrate greater resistance and be less/not affected by mental fatigue [8]. In addition it was expected badminton players would outperform controls on the visuomotor task as well as on the Stroop task [8].

4.3 Methods

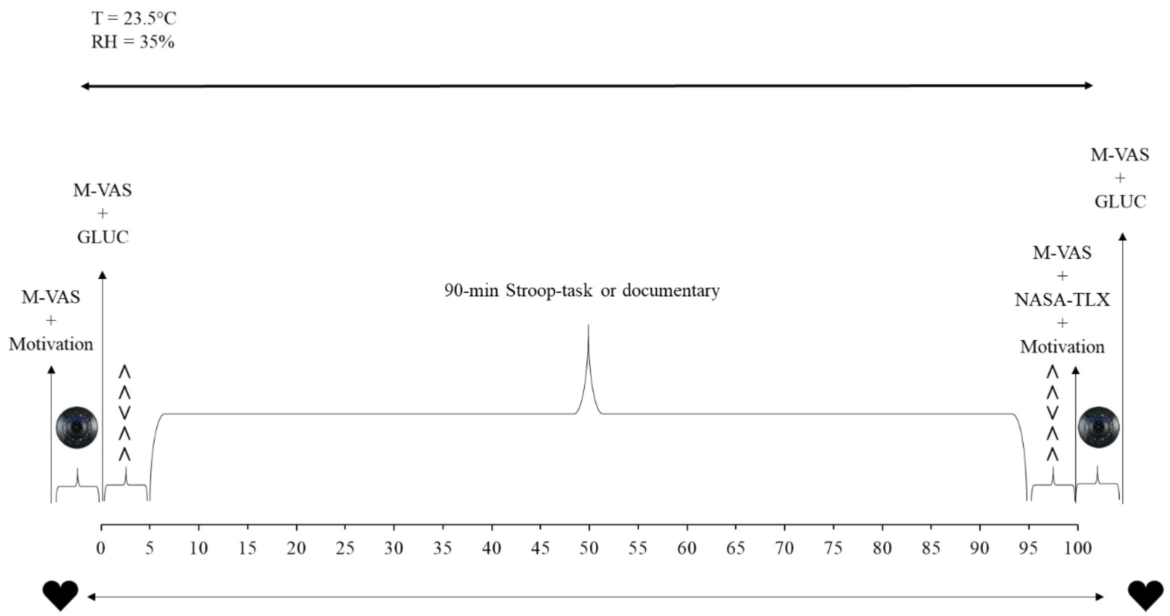
4.3.1 Participants and ethical approval

An a priori sample size calculation based on the results reported in the study of Martin et al. [8] (reported effect size of the interaction between condition and group was η_p^2=0.293) revealed – with α set at 0.05 and an actual power of 0.85 – that a total of 8 participants were needed in each group to observe a similar interaction effect. Twelve healthy controls and ten healthy badminton players volunteered to participate in this study, and eventually, eleven healthy controls (mean ± SD; age: 25 ± 4y, stature: 1.69 ± 0.07m, body mass: 70.2 ± 13.8kg, 6 females, 5 males) and nine healthy badminton players (mean ± SD; age: 23 ± 3y, stature: 1.73 ± 0.11m, body mass: 67.0 ± 12.8kg; 4 females, 5 males) were included in the data analyses (see *Results* for reason of dropout). Each participant gave written informed consent prior to the study and were naive of its aims and hypotheses. Controls were not engaged in any kind of regular physical activity during the last 5 years, badminton players competed at national and/or international level and performed ≥2/3 badminton training sessions per week and had ≥8 years badminton experience. The experimental protocol and procedures were approved by the Research Council of the Vrije Universiteit Brussel, Belgium. The participants were given instructions to sleep a similar amount of time before each trial (at least 7 hours), refrain from the consumption of caffeine and alcohol and not to practice vigorous physical activity the day before and from each visit. In addition, participants were asked to have the same meal the morning of each trial and the use of any kind of medicinal products during and between the trials was prohibited. If participants could not meet these standards they were excluded from the study.

4.3.2 Experimental protocol

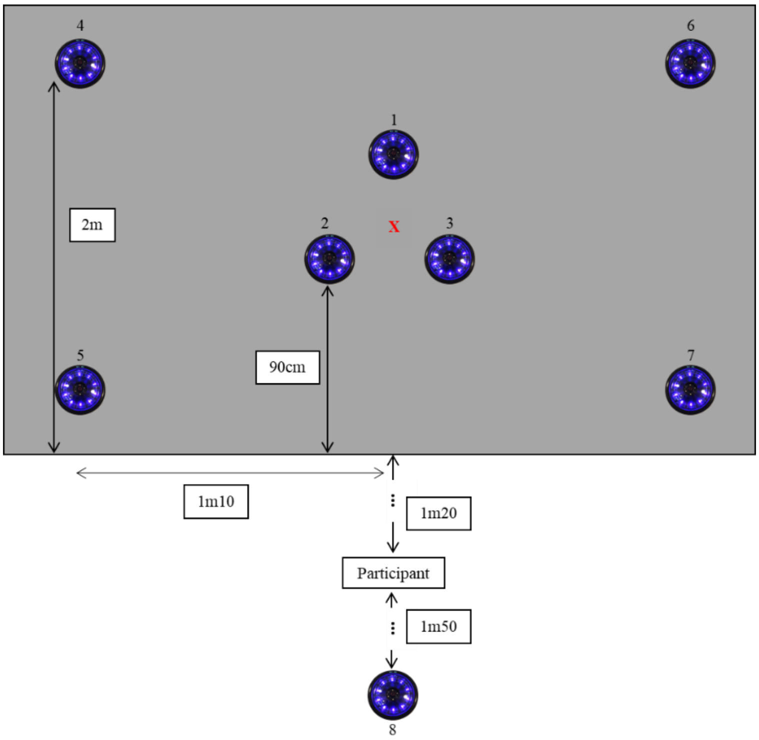
Participants were asked to report to the lab for 3 consecutive trials, which were all conducted at the same time of day (in the morning) and were separated by at least 3 days to ensure full recovery. The first trial was a familiarization trial, followed by an experimental trial (MF) and a control trial (CON). All trials were conducted in thermoneutral conditions (23.5°C, humidity 35%) and took ~2h to complete. MF and CON were completed in a randomized, crossover manner. See Fig.1 for a complete overview and timeline of the protocol. Participants had to perform a baseline visuomotor task (see *visuomotor task*), followed by a Flanker task (see *Flanker task*). Next, they performed either a 90-min Stroop task (MF; see *mental fatigue task*) or watched a 90-min documentary (CON; see *control task*). Immediately thereafter, the Flanker task and the visuomotor task were completed again. In the familiarization trial participants completed all procedures as if it was an experimental trial (see Fig. 1), except for the 90-min cognitive task. Instead of the 90-min cognitive task, participants performed a 30-min version of the Stroop task to familiarize with all instructions.

Fig. 1 Protocol timeline (min). Participants had to perform a first visuomotor task. After completing the baseline visuomotor task, participants sat down and completed a 90-min mentally fatiguing task or a 90-min control task, that was preceded and immediately followed by a 3-min Flanker task. Immediately (~2min) after the second Flanker task a second visuomotor task was performed. T = ambient temperature; RH = relative humidity; MFS = self-reported mental fatigue; Motivation = success motivation and intrinsic motivation scales developed and validated by Matthews et al. [18]; NASA-TLX = the National Aeronautics and Space Administration Task Load Index; GLUC = blood glucose; = heart rate; = visuomotor task; = 3-min Flanker task



Visuomotor task To develop a visuomotor task, Fitlight-hardware and software was used (http://www.fitlighttraining.com/). Seven lights were set up against a wall (see Fig.2) and illuminated for 2s, one after the other in a set sequence. These lights colored, similar to the Stroop-stimuli, red, blue, green or yellow. If a light turned red, green or yellow (i.e. simple stimuli) participants had to put out the light as fast as possible by passing before the light with the left or right hand within a range of 5cm. However, if a light turned blue (i.e. complex stimulus), participants were instructed not to respond to the stimulus on the wall. Instead they had to turn around and put out another light lying behind them on the floor (1m50; see Fig.2). After each stimulus, participants were instructed to return to their starting position (perpendicular to light no.1, 1m20 away from the wall and with both feet ~30cm apart and on the same line), which was indicated on the floor, and focus again on the fixation cross (see Fig. 2). Each color was presented 16 times, yielding a total of 64 stimuli. The sequence in which the colors appeared was programmed randomly (www.randomization.com), as was the location of the light in which the color appeared. The inter-stimulus time varied between 3, 4, 5 or 6s and each inter-stimulus time was randomly used 16 times. Total task duration was approximately 6min30s. To avoid learning effects each visuomotor task was different as the pre-programmed sequence would always start randomly somewhere within the sequence. Accuracy and response time (RT) were collected to assess performance.

Fig. 2 Overview of the visuomotor task.



Flanker task In the Flanker task participants were instructed to respond as quickly and accurately as possible to the direction of a target arrow while ignoring two flankers on each side. See Van Cutsem et al. [12] for a detailed description. The task used in the present study only differed from the task used in the study of Van Cutsem et al. [12] in that sense that all trials presented in the present task were incongruent (e.g., < < > < <), requiring a great level of inhibitory control. The second Flanker task was performed 20s after completion of the 90-min mentally fatiguing task or control task. To assess performance on the Flanker task accuracy and RT were collected. Participants were, based on the assumption that they were already fatigued or not adequately familiarized [13], excluded from the analysis if they were not able to reach a minimum accuracy level of 90% in the first Flanker task (i.e. the baseline performance).

Mental fatigue task A modified Stroop task of 90min, partitioned in 8 blocks of 252 stimuli, was used as the mentally fatiguing task. This 90-min task was continuous with no rest breaks (i.e. participants had no knowledge of the existence of the 8 task blocks). The inclusion of the 8 task blocks/epochs allows the researcher to examine performance impairment (i.e. accuracy and RT) as a function of time-on-task which is a behavioral indicator of cognitive fatigue [7, 14]. In this task, four colored words (“red”, “blue”, “green” and “yellow”) were presented one at a time on a computer screen. If the ink color of the word was yellow, green or blue the participants were required to indicate the color of the word, ignoring the meaning of the word itself (i.e. ‘color’ stimuli). If however, the ink color was red, the button to be pressed was the button linked to the real meaning of the word (i.e. ‘meaning’ stimuli), not the ink color (see Van Cutsem et al. [15] for a detailed description). The word presented and its ink color were randomly selected by the computer (100% incongruent), with all incongruent word-color combinations being equally common (meaning, in each block 63 words were presented in the color red, yellow, green and blue). Prior to each 90-min Stroop task time-keeping devices such as watches and cell phones were surrendered and during the task participants did not receive any feedback on performance or time lapsed. Participants were, based on the assumption that they were already fatigued or not adequately familiarized [13], excluded from the analysis if they were not able to reach a minimum accuracy level of 70% in the first or second time interval of the task.

Control task In the control task participants had to watch a documentary ((A) “Planet earth” (BBC Worldwide, 2006), (B) “When we left earth – the NASA missions” (Discovery entertainment, 2008), and (C) “ooggetuigen”: (Ca)“Honden”, (Cb) “Haaien”, or (Cc) “Vulkanen” (BBC Worldwide, 2007)). In order to promote engagement and avoid boredom participants were given the choice: 1 chapter from (A) and 1 disc “ooggetuigen” or 1 disc from (B), for a total of 90min. These documentaries were chosen based on their emotionally neutral, yet engaging content.

Physiological and subjective measurements During the entire protocol a researcher was sitting behind the participant to ensure compliance with the intervention. Participants were equipped with a heart rate monitor to continuously record heart rate (HR). Blood glucose was measured before the 90-min task and immediately after finishing the second visuomotor task by extracting 0.6-µl of blood from the right earlobe (CONTOUR LINK Medtronic Blood Glucose Meter System, Bayer, Basel, Switzerland). Subjective psychological assessment took place with a mental fatigue-visual analogue scale (MFS) [16], the National Aeronautics and Space Administration Task Load Index (NASA-TLX; [17]) and the success motivation and intrinsic motivation scales developed and validated by Matthews [18]. The validity and reliability of a visual analogue scale (0-10cm) to assess fatigue was demonstrated by Lee et al. [16], MFS posed the question ‘How mentally fatigued do you feel?’, and ranged from ‘not at all’ to ‘completely exhausted’ [16]. The NASA-TLX scale assesses subjective workload and was taken after finishing the 90-min task. Motivation related to the visuomotor task was measured by the scales of Matthews [18] and was assessed before both visuomotor tasks (see Fig.1).

4.3.3 Statistical analysis

All data are presented as means ± standard deviation (SD) unless stated otherwise. The Shapiro-Wilk test was used to test the normality of the data, sphericity was verified by the Mauchly's test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted with the Greenhouse-Geisser procedure.

A two-way mixed (2x2) ANOVA was used to assess the effects of group and condition on each NASA-TLX subscale and on square root transformed mean HR. A three-way mixed (2x2x2) ANOVA was used to assess the effects of group, condition and time on intrinsic and success motivation towards both visuomotor tasks. Blood glucose (2x2x2) and MFS (2x2x4) responses were analyzed with three-way mixed ANOVAs, with factors group, condition and time. A three-way mixed (2x8x2) ANOVA was used to test the effect of group (badminton players vs controls), time (first to eighth block) and stimuli (meaning vs color) on RT and square root transformed accuracy during the mental fatigue task. Three-way mixed (2x2x2) ANOVA was used to test the effects of group, condition and time on RT and square root transformed accuracy during the Flanker tasks. A four-way mixed (2x2x2x2) ANOVA was used to test the effects of group, condition, time and stimuli (simple vs. complex) on RT during the visuomotor tasks. Wilcoxon signed ranks tests were employed to assess the effect of condition and time on visuomotor task accuracy in each group and each stimulus type.

If significant interaction effects including the factors condition and time in the four-way, three-way or two-way mixed ANOVAs were observed, subsequent three-way or two-way mixed ANOVAs or paired t-tests were performed to elucidate the main effect of condition and time. If no significant interaction effects, including the factors condition and time, in the four-way, three-way or two-way mixed ANOVAs were observed, main effects of condition and time were immediately studied and further interpreted through pairwise comparisons with Bonferroni correction.

In order to assess whether badminton players possess superior inhibitory control and task switching-ability compared to controls, and to control for the potential confounding effect of differences in resistance to mental fatigue, planned comparisons were executed in the first time interval of the Flanker task, Stroop task and visuomotor task.

Significance was set at <0.05 for all analyses, which were conducted using the Statistical Package for the Social Sciences, version 23 (SPSS Inc., Chicago, IL, USA).

4.4 Results

4.4.1 Manipulation checks

All participants except two (1 control and 1 badminton player) reached the required minimum performance level of 70% in one of the two first time intervals during the Stroop task and were included in the data-analysis.

Behavioural

The effect of time on the transformed accuracy-data differed in both types of stimuli (time x stimuli; $F(7,126)=2.1$; $p=0.050$), group did however not affect the effect of time. Within the color stimuli accuracy was similar over time ($F(4.2,79.3)=0.5$; $p=0.753$; see Fig. 3). Within the meaning stimuli a decrease in accuracy over time ($F(7,133)=2.4$; $p=0.023$; $\eta^2=0.11$; See Fig. 3) was found. In terms of RT it was shown that participants performed faster in time independent of group in both the color stimuli ($F(7,133)=3.5$; $p=0.002$; $\eta_p^2=0.16$; see Fig. 4) and the meaning stimuli ($F(3.9,74.2)=12.7$; $p<0.001$; $\eta_p^2=0.4$; see Fig. 4). Regarding transformed accuracy on the Flanker task, no effect of condition, time or group was observed. RT on the Flanker task was observed to increase in time independent of group and condition (PRE: 362 ± 36 ms → POST: 371 ± 35 ms; $F(1,18)=7.2$; $p=0.015$; $\eta_p^2=0.29$). In addition, the planned comparison in the first time interval of the Stroop task and the first Flanker task demonstrated that there was no difference in accuracy or RT between badminton players and controls in both tasks.

Fig. 3 Square root transformed accuracy during the 8 blocks of the Stroop task. * denotes a significant main effect of time on the meaning stimuli in both badminton players and controls (p<0.05). Data are presented as means ± SE.

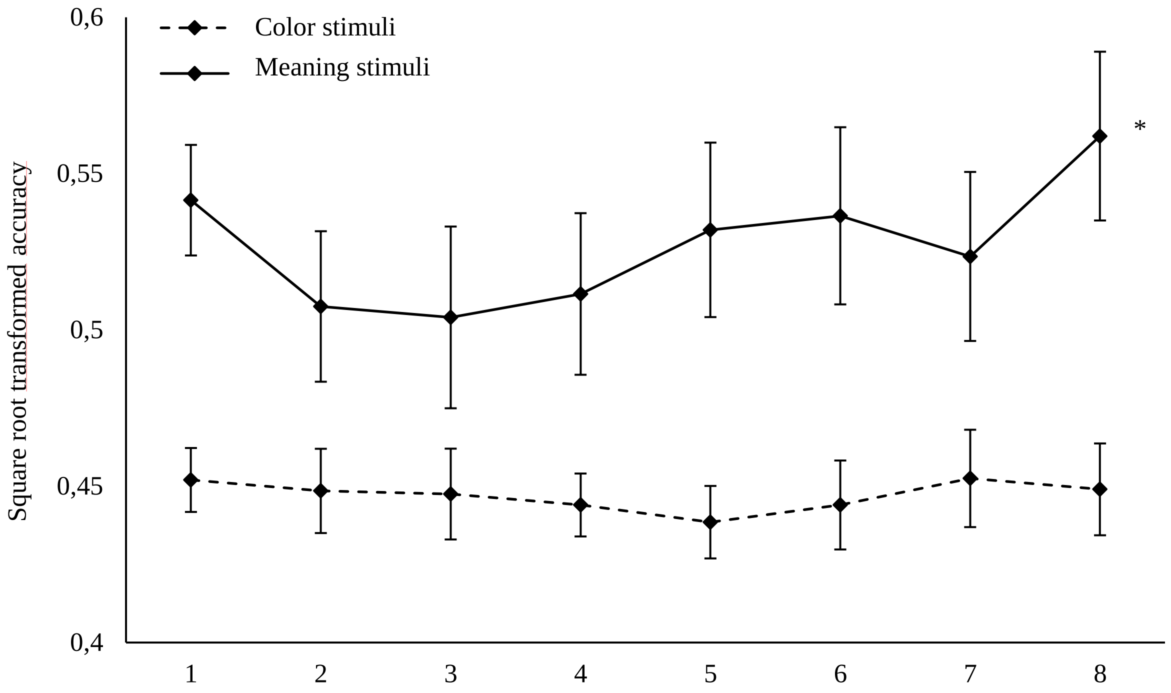
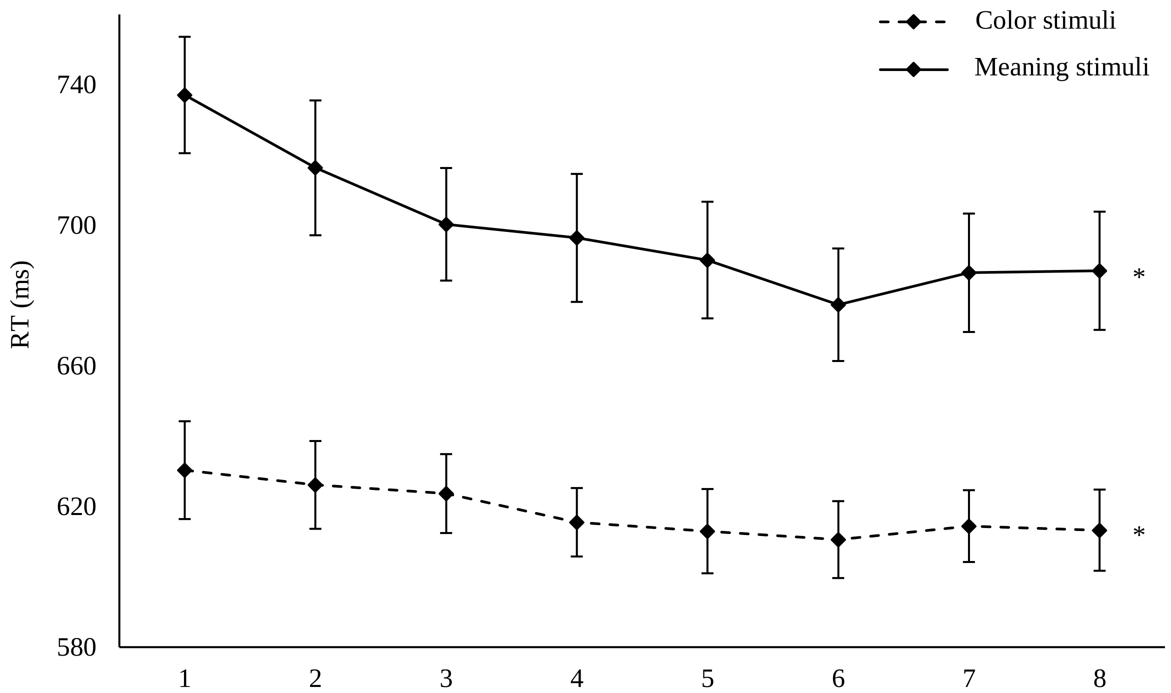


Fig. 4 Response time (RT) during the 8 blocks of the Stroop task. * denotes a significant main effect of time in both badminton players and controls (p<0.05). Data are presented as means ± SE.



Subjective

Overall subjective mental fatigue was higher ($F(1,18)=5.6$; $p=0.029$; $\eta_p^2=0.24$) in MF (44 ± 17) compared to CON (38 ± 12), independently from group. Subjective mental fatigue was higher after both the Stroop and control task compared to before the respective tasks ($F(3,54)=34.7$; $p<0.001$; $\eta_p^2=0.66$; pre control and Stroop task = 30 ± 18; post control and Stroop task = 63 ± 17). In both badminton players and controls, the mental demand, physical demand, temporal demand, effort and frustration subscale of the NASA-TLX were perceived as higher after the Stroop task compared to the control task ($F(1,18)\geq 8.1$; $p\leq 0.011$; $\eta_p^2\geq 0.41$). Only the performance subscale of the NASA-TLX was not perceived as different between both conditions. No difference was observed in intrinsic and success motivation towards both visuomotor tasks.

Physiological

Transformed mean HR was significantly ($F(1,18)=8.9$; $p=0.008$; $\eta_p^2=0.33$) higher during the Stroop task (8.8 ± 0.6; absolute value=77 ± 9 bpm) compared to during the control task (8.5 ± 0.5; 72 ± 9 bpm) independently from group. Blood glucose levels decreased ($F(1,17)=10.5$; $p=0.005$; $\eta_p^2=0.38$) from the beginning of the protocol (93.8 ± 6.7 mg/dl) to the end (86.6 ± 7.6 mg/dl).

4.4.2 Performance on the visuomotor task

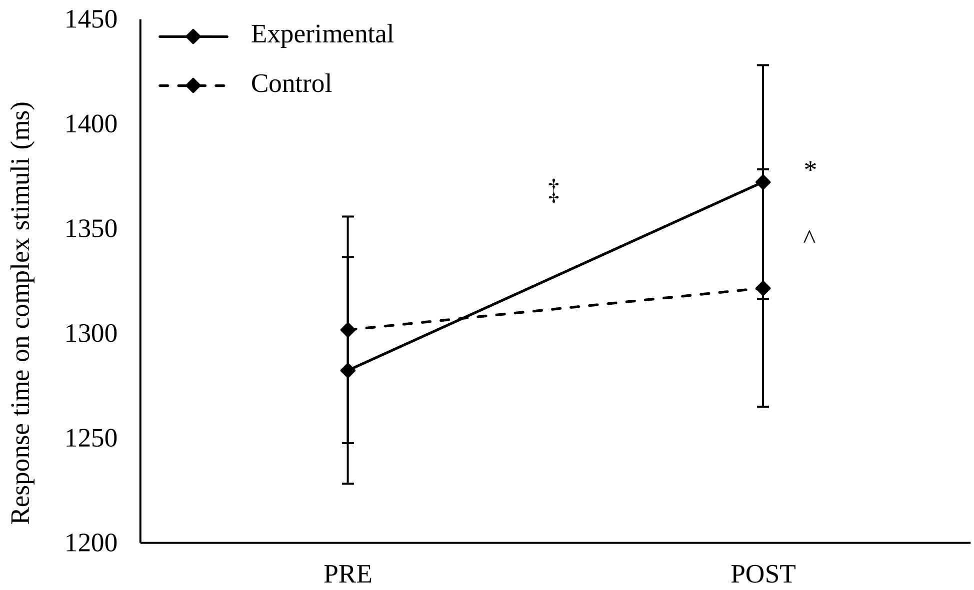
Accuracy

Non-parametric testing showed that there was no effect of condition or time on accuracy.

Response time

The effect of the mentally fatiguing task on RT during the visuomotor task was independent of group. In contrast, type of stimulus did affect the effect of the mentally fatiguing task (condition x time x stimuli; $F(1,18)=8.0$; $p=0.011$). Within the complex stimuli an interaction between the effects of condition and time was present (condition x time; $F(1,19)=10.0$; $p=0.005$). Participants got significantly slower in time only in MF ($t(19)=-4.4$; $p<0.001$; $d=0.98$; PRE: 1282 ± 242 ms; POST: 1372 ± 249 ms; see Fig. 5), while the effect of condition ($t(19)=2.2$; $p=0.040$; $d=0.49$; 1372 ± 249 ms; CON: 1322 ± 253 ms; see Fig. 5) was only present in the second visuomotor task. Within the simple stimuli only a main effect of time ($F(1,19)=25.9$; $p<0.001$; $\eta_p^2=0.58$) was observed, independent of condition. The planned comparison in the first visuomotor task demonstrated that the controls (1299 ± 227 ms) performed slower than the badminton players (1109 ± 251 ms), independently from stimuli and condition ($F(1,18)=6.3$; $p=0.022$; $\eta_p^2=0.26$).

Fig. 5 Response time (RT) on the complex stimuli (independent of group; n=20) during the visuomotor task (pre and post). ‡ denotes a significant condition x time interaction ($p<0.05$). * denotes a significant main effect of time in MF ($p<0.05$). ^ denotes a significant difference between MF and CON in the post visuomotor task. Data are presented as means ± SE.



4.5 Discussion

To our knowledge this is the first study that assessed the effect of mental fatigue on open skill-visuomotor performance in badminton players and controls. The most important findings were: (I) Badminton players demonstrated a superior visuomotor performance compared to controls; (II) Mental fatigue decreased open skill-visuomotor performance in controls as well as badminton players.

4.5.1 Manipulation checks

The behavioral, subjective and physiological measures confirmed higher mental exertion in the Stroop task, indicating a greater state of mental fatigue was successfully induced in MF compared to CON. Both subjective (higher perceived mental demand) and physiological (higher mean HR; [19]) measures confirmed that the Stroop task was more mentally demanding than watching the documentary. Moreover, in the Stroop task the often found decrease in accuracy in time was observed in the meaning stimuli in both the badminton players and controls [20, 21]. Performance on the Flanker task confirmed that cognitive capacity decreased in MF. Participants performed slower on the second Flanker task compared to the first. However, also in CON a similar deterioration in RT during the second Flanker task was observed. This indicates that the induced mental fatigue did not affect Flanker performance in the present study, or, that 90min watching a documentary might also have induced a certain degree of mental fatigue. Subjectively a higher feeling of mental fatigue was reported in MF compared to CON in both badminton players and controls.

4.5.2 Visuomotor task performance

On average, participants responded 7% slower on the complex stimuli (i.e. blue stimuli) compared to baseline in MF, while in CON no significant impairment was found. These results show that mental fatigue particularly impaired the RT to the complex stimuli, rather than the simpler stimuli (i.e. green, red and yellow stimuli), in both the badminton players and the controls. This is in accordance with previous studies on the effect of mental fatigue on cognitive performance [22-24], showing that executive control (i.e. the control to overrule an automatic response) is compromised by mental fatigue, but more automatic cognitive processing is relatively insensitive to this state.

According to the proposed models attempting to explain the link between mental fatigue and human performance [25], similarities across the cognitive and the physical task should account for the observed mental fatigue-induced decrease in sport-specific psychomotor performance. In both the 90-min Stroop task and the 7-min visuomotor response task response inhibition was an important executive function determining task performance. In the Stroop task response inhibition was necessary for 100% of stimuli, while in the visuomotor task this function was employed for 25% of the stimuli. Both tasks also worked with a general response rule and an exceptional response rule, meaning that participants had to switch rules depending on specific color features of the stimuli. This task switching ability was necessary in 25% of the stimuli, as 25% of the stimuli presented in the Stroop task and in the visuomotor task contained the specific feature (i.e. in the Stroop when the letters of the word were colored in red; in the visuomotor task when the pad lighted op in the color blue) that indicated that participants had to switch to the exceptional rule in order to respond correctly. These two executive functions, response inhibition and task switching ability, represent two important similarities across the cognitive and the visuomotor task that might explain why carry-over effects were observed.

In the present study mental fatigue did not affect Flanker performance or performance on the color stimuli in the Stroop task (i.e. both response inhibition-measures). As such, the effect of mental fatigue on response inhibition appears to be ambiguous. In contrast, task-switching ability was specifically assessed by accuracy and RT on the meaning stimuli in the Stroop task and RT on the blue stimuli in the visuomotor task. These measures specifically assessed task-switching ability due to their low appearance probability in comparison with the other stimuli in both tasks (i.e. the low appearance probability of both stimuli leads to a high relative rate of switch trials; [26]), and performance on both these measures was impaired by mental fatigue. This reasoning puts forward task-switching as the main executive function that was deteriorated by mental fatigue and confirms the previously reported findings of a mental fatigue-induced impairment in task-switching ability [26-28]. Moreover the present findings add that this impairment also persists in a more sport-specific setting.

4.5.3 Badminton players vs controls

Badminton players only outperformed the controls on the visuomotor task. These findings lead to the conclusion that badminton players did not have a superior inhibitory control or task switching-ability compared to controls, rather badminton players demonstrated a superior visuomotor RT. This contrasts the observed superior inhibitory control in elite cyclists in the study of Martin et al. [8]. In addition, unlike in the study of Martin et al. [8], the badminton players in the present study did not demonstrate a greater resistance to mental fatigue than controls. Martin et al. [8], and also other studies [2-4], however already indicated that although superior inhibitory control might be a psychobiological characteristic of athletes, this does not mean they are immune to mental fatigue. It seems this statement is substantiated in the present study, as unlike the 30-min Stroop task used in the studies of Martin et al. [8] and Clark et al. [9] to induce moderate mental fatigue, a 90-min Stroop task was employed to induce more severe mental fatigue. This might explain why, in our study, mental fatigue impaired visuomotor performance not only in controls but also in badminton players. Another factor that could explain why we cannot substantiate the results of Martin et al. [8] is the fact that the badminton players included in the present study were trained (see *participants characteristics*), but not elite. Therefore, caution is warranted in concluding that level of training does not improve the resistance to mental fatigue.

Badminton players thus did not demonstrate superior inhibitory control or task switching-ability compared to controls. They did however demonstrate a superior visuomotor RT, hereby substantiating the statement of Hülsdünker et al. [29] that open skill-athletes typically outperform non-athletes on visuomotor RT-tasks. Hülsdünker et al. [29] assessed why this is the case and concluded that the superior visuomotor performance originates from faster visuomotor transformation in the premotor and supplementary motor cortical regions rather than from earlier perception of visual signals in the visual cortex.

4.5.4 Practical applications

The present study shows that mental fatigue impairs open skill-visuomotor performance in athletes and should thus be taken into account by trainers and coaches to optimize sport performance (e.g. avoid long tactical talks prior to competition). This stresses the need for future research to develop interventions (e.g. cognitive training, mouth rinsing, …) that might be suitable to increase resistance to mental fatigue [15]. In addition the newly developed open skill-visuomotor task is shown to be a sensitive tool to assess the performance-impairing effect of mental fatigue and subsequently provides a perhaps more suitable alternative, besides the traditional psychological cognitive tests (e.g. Flanker task), for trainers and coaches who want to evaluate the individual mental fatigue-resistance of their athletes.

4.6 Conclusion

Mental fatigue manifested in both badminton players and controls after a 90-min Stroop task and impaired open skill-visuomotor performance in both groups. More specifically participants responded on average 7% slower on the complex stimuli in the visuomotor task compared to baseline in MF. Firstly, this shows that athletes are indeed not immune to mental fatigue. Secondly the present results substantiate mental fatigue does not only impair endurance sports, but also impairs open skill-visuomotor performance.

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The authors declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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Conflict of interest

No conflict of interest is declared by the authors.

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Chapter 5: Counteracting mental fatigue

<u>A caffeine-maltodextrin mouth rinse counters mental fatigue.</u>

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5.1 Abstract

Introduction: Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity that has negative implications on many aspects in daily life. Caffeine and carbohydrate ingestion have been shown to be able to reduce these negative effects of mental fatigue. Intake of these substances might however be less desirable in some situations (e.g. restricted caloric intake, Ramadan, …). Rinsing caffeine or glucose within the mouth has already been shown to improve exercise performance. Therefore we sought to evaluate the effect of frequent caffeine-maltodextrin (CAF-MALT) mouth rinsing on mental fatigue induced by a prolonged cognitive task.

Methods: Ten males (age:23±2y, physical activity:7.3±4.3h/week, low CAF-users) performed two trials. Participants first completed a Flanker task (3 min), then performed a 90-min mentally fatiguing task (Stroop task), followed by another Flanker task. Before the start and after each 12.5% of the Stroop task (8 blocks) subjects received a CAF-MALT mouth rinse (MR;0.3g/25ml CAF;1.6g/25ml MALT) or placebo (PLAC;25ml artificial saliva).

Results: Self-reported mental fatigue was lower in MR (p=0.017) compared to PLAC. Normalized accuracy (accuracy first block=100%) was higher in the last block of the Stroop in MR (100.4 ± 1.6%; p=0.032) compared to PLAC (91.0 ± 3.5%). P2-amplitude in the dorsolateral prefrontal cortex (DLPFC) decreased over time only in PLAC (p=0.017).

Conclusion: Frequent mouth rinsing during a prolonged and demanding cognitive task reduces mental fatigue compared to mouth rinsing with artificial saliva.

Keywords: Cognitive fatigue, Mouth Rinse, Electroencephalography, Cognitive performance

5.2 Introduction

Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity [1, 2] with subjective and objective manifestations [for an extensive definition see Van Cutsem et al. [3]]. Subjectively, increased feelings of tiredness and lack of energy are reported [4], as well as a decrease in alertness [5]. Objectively, mental fatigue can also result in a decline in cognitive performance [6] and alterations in brain activity [7, 8]. Multiple studies have shown a negative effect of mental fatigue on many aspects of daily life [3, 9, 10]. In the workplace for example, mental fatigue has been found to predict an increased risk of error of surgeons [9], while during military operations it has been found to impair physical and cognitive ability [11]. In daily life, fatigue can ensue after only 60 min of driving and is associated with a difficulty in maintaining skilled driving behaviour [12]. In addition it is also one of the most common symptoms experienced by individuals with neurological disorders [10] and recognized as one of the most common and distressing side effects of cancer and its treatment [13].

Therefore, an interest in how to reduce mental fatigue has emerged. Caffeine (1,3,7-trimethylxanthine) is the most commonly consumed psychoactive stimulant in the world, and is often found to enhance human vigilance and mental alertness [14]. Consequently the intake of caffeine, with its ability to cross the blood-brain barrier and block the adenosine receptors in the brain [15, 16], was the first mental fatigue countermeasure to be tested and found to be successful [16, 17]. Furthermore carbohydrate ingestion has also been found to positively affect mental fatigue [18]. There is even some evidence that, when administered together, interactions between glucose and caffeine counteract mental fatigue even more successful [18]. A combination of caffeine and carbohydrates (e.g. glucose) is the main ingredient of the energy drinks that have become so popular in recent years to enhance alertness and both physical and cognitive performance [18, 19].

Caffeine, as well as carbohydrate intake, might however come with some unwanted side-effects. Caffeine-intake for example, can cause tremors, nausea, nervousness, increased levels of anxiety or gastrointestinal distress [17]. In addition it may also adversely affect sleep patterns [17]. Ingesting carbohydrates might also be forbidden (e.g. during Ramadan) or unwanted for health reasons (e.g. diabetes and obesity), especially in the form of energy drinks [20]. Therefore, an alternative to caffeine and/or carbohydrate ingestion may be useful to people who want to reduce their mental fatigue without the potential negative effects of caffeine and carbohydrate ingestion.

One of the alternatives to caffeine and/or carbohydrate ingestion is mouth rinsing. Mouth rinsing is a nutritional strategy that involves rinsing of substrates within the mouth for several seconds (5–20 s) without ingesting the solution, and thus avoids the negative side-effects of intake of the substance. The rinsing of a solution containing carbohydrates, caffeine or both, has been shown to reduce fatigue and performance during exercise [21-23]. The combination of both carbohydrates and caffeine has even been observed to have an additive positive effect compared to the separate use of both substances [22]. However, to the best of our knowledge, the use of mouth rinsing with both carbohydrates and caffeine as a mental fatigue countermeasure has never been tested. Therefore, we sought to assess the effects of frequent mouth rinsing with a caffeine-maltodextrin (CAF-MALT) solution during a prolonged and demanding cognitive task (serial mouth rinsing) on various markers of mental fatigue. We hypothesized that the subjective markers (i.e. self-reported mental fatigue), objective markers (decline in cognitive performance) and brain activity alterations typically associated with mental fatigue (i.e. a decrease in P2- and P3-

amplitude and an increase in θ and α activity) would be positively counteracted by the serial CAF-MALT mouth rinsing.

5.3 Methods

5.3.1 Subjects and ethical approval

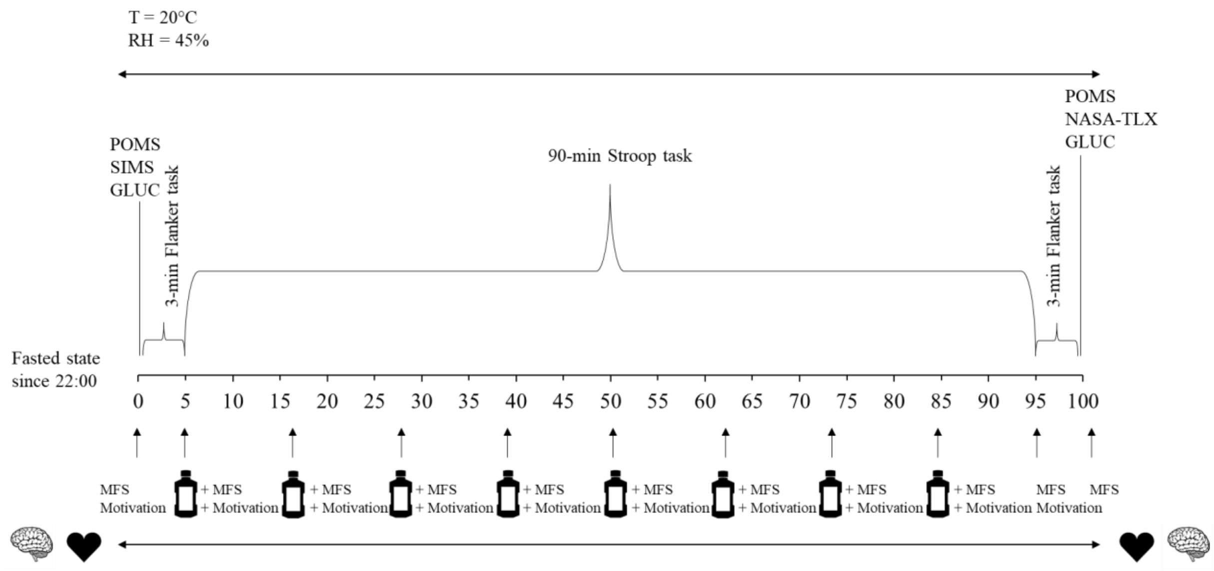
Ten active healthy male students volunteered to participate in this study (mean ± SD; age: 23 ± 2 y, physical activity hours(h)/week: 7.3 ± 4.3 h/week). They were all low caffeine users (caffeine usage/day: 101 ± 97 mg/day; assessed with a caffeine consumption questionnaire) and none had any known mental or somatic disorder. Each subject gave written informed consent prior to the study. Experimental protocol and procedures were approved by the Research Council of the Vrije Universiteit Brussel, Belgium.

5.3.2 Experimental protocol

Subjects were asked to return to the lab for 3 consecutive trials. The first trial was a familiarization trial (to get to know the routine, the equipment and to avoid learning effects), followed by two experimental trials [i.e. a mouth rinse-trial (MR) and a placebo-trial (PLAC)] , all separated by at least 6 days (mean: 8 days, SD: 3days) to ensure full recovery. All trials were conducted in thermoneutral conditions (20°C, humidity 45%) and took approximately 2 h (Fig. 1). Preceding the beginning of the familiarization trial subjects were asked about their health status, were given written instructions describing all procedures related to the study and got the opportunity to ask questions. Subjects were excluded if they presented with any medical history, family history or medication or drug use that would prevent them from safely completing the experiment.

After an overnight fast, subjects entered a sound-insulated and dim lit laboratory at the same time of day. Subjects were seated in a comfortable chair, wore earplugs, and kept the same body posture during the entire experiment. The MR- and PLAC-trial were completed in a double-blinded, randomized, crossover protocol. To determine the effect of the mouth rinse solutions on brain activity, 32 active Ag/AgCl electrodes were attached on the subjects' head preceding each trial (Acticap, Brain Products, Munich, Germany), according to the "10–20 International System" [24]. EEG was continuously measured during all cognitive tasks (see EEG recordings for more information). All trials began with one baseline Flanker task (duration 3 min), followed by a 90-min mentally fatiguing task (in the familiarization trial this task was performed for 30 min) and ended with the same 3-min Flanker task as in the beginning (Fig. 1).

Fig. 1 Protocol timeline (min). T = ambient temperature; RH = relative humidity; POMS = profile of mood states; SIMS = situational & intrinsic motivation scale; GLUC = blood glucose; MFS = self-reported mental fatigue; = mouth rinse; = Electroencephalography; = heart rate



Flanker task In the Flanker task all cues were incongruent, meaning the flanking arrows pointed in the opposite direction as the target arrow (e.g. < < > < <), requiring a great level of inhibitory control over the flanker arrows in order to execute an accurate response. Each array of arrows was focally presented in white text for 200 ms on a black background with a variable inter-stimulus interval of 1000, 1200, 1400, or 1600 ms. One hundred and twenty trials were presented randomly with right and left target arrows occurring with equal probability. Total Flanker task duration was approximately 3 min. Participants were instructed to respond as quickly and accurately as possible to the direction of a target arrow while ignoring two flankers on each side. The second Flanker task was performed exactly 20 s after completion of the 90-min mentally fatiguing task to avoid a rest break influencing the effect of the mentally fatiguing task on the Flanker task performance. To assess performance on the Flanker task accuracy and response times (RT) were collected.

Mentally fatiguing task A modified Stroop task [25, 26] of 90 min, partitioned in 8 blocks of 252 stimuli, was used as mentally fatiguing task. Between each block a small intersection of 20 stimuli was implemented (participants perceived no stop in the Stroop task) that, without the participants' knowing, was not accounted for in the accuracy-, RT- and EEG-analysis (see *MR protocol* for the purpose). The Stroop task is a task that requires inhibition and selective attention on controlled processes [27]. In this task, four coloured words ("red", "blue", "green" and "yellow") were presented one at a time on a computer screen. The participants were required to indicate the colour of the word (i.e. 'colour' stimuli), ignoring the meaning of the word itself. If however, the ink colour was red, the button to be pressed was the button linked to the real meaning of the word, not the ink colour (i.e. 'meaning' stimuli). The word presented and its ink colour were randomly selected by the computer (100% incongruent), with all incongruent word-colour combinations being equally common (meaning, in each block 63 words were presented in the colour red, yellow, green and blue). Each word was presented on screen in 34 point font for 1000 ms with a variable inter-stimulus interval of 1100, 1500 or 1900 ms, with each inter-stimulus interval being equally common. Subjects were instructed to respond as quickly and accurately as possible. Performance was assessed similarly to the Flanker task and a €50-reward for the best mean performance on the mentally fatiguing task in both conditions was offered. This should minimize the negative effects of poor motivation and disengagement on Stroop-performance.

MR solutions The MR solutions were bottled (volume 25 ml) and flavoured with an amount of sodium salt of saccharin (0.03 g PLAC MR, 0.45 g CAF-MALT MR) by an independent pharmacy to blind the caffeine-taste, and stored in the dark at room temperature. PLAC MR consisted of the main ionic components of saliva, meaning distilled water containing 25 mmol KCl (0.047 g) and 2.5 mmol $NaHCO_3$ (0.005 g) [28], which is tasteless and odour-free. This 'artificial saliva' solution was employed, instead of pure water, to minimize the activation of cortical taste areas which are sensitive to water in the mouth [29]. The same solution was used for CAF-MALT MR with the addition of 1.2% w/v CAF powder (0.3 g) and 6.4% w/v MALT powder (1.6 g).

MR protocol Before the start of the Stroop and every 12.5% completion of the 90 min [30] participants had to rinse their mouth with a given solution. A block of 20 stimuli was presented during and immediately after the mouth rinse. At this time the accuracy and RT data were collected, but not included in any analysis. This created the urge to keep on performing and avoided the subjects regaining motivation due to a rest-break. The subjects had to rinse the MR solution for 10 s before expectorating it into a waste container. The MR-solution was provided in a 30 ml cup, the researcher poured the drink in the mouth of the participant so the participant did not have to detach his hands from the keyboard to be able to rinse the solution in the mouth and expectorate it afterwards in another cup. The subjects' subjective rating of the pleasantness of the bitterness/sweetness of the taste stimuli was also assessed after each trial using a rating scale [28] (+2= very (pleasant), 0= neutral, and -2= very (unpleasant)).

During the entire protocol subjects were equipped with a heart rate monitor (HR; Polar RS400, Polar Electro Oy, Kempele, Finland). Before and after the entire protocol blood glucose concentration was assessed (Bayer, Contour Next Link, Medtronic, Vienna, Austria) by collecting capillary blood at the ear lobe. Subjective psychological assessment took place before the start of the cognitive tasks with the Situational Motivation Scale (SIMS) to assess participants' motivation towards the upcoming 90-min Stroop task [31], during the cognitive tasks with a mental fatigue- and motivation-scale (0-100) and after the cognitive tasks with the National Aeronautics and Space Administration Task Load Index [NASA-TLX; [32]] and the Profile Of Mood States (POMS). The SIMS was filled in before the start of the first Flanker task and is a 16-item self-report inventory, which is designed to measure intrinsic motivation, identified regulation, external regulation and amotivation. Both a mental fatigue and motivation-scale (0-100) were taken before and after both Flanker tasks and within each timeframe of the 20 unrecorded stimuli during the mentally fatiguing task. These scales assessed respectively how mentally fatigued the subject was feeling (MFS; '0 = not at all' to '100 = completely exhausted') and how motivated the subject was feeling towards the next block in the Stroop task ['0 = not at all' to '100 = extremely motivated' [7]]. For the subjects to be able to keep their hands in place on the keyboard they indicated their level of mental fatigue and motivation vocally by announcing a number between 0 and 100. The NASA-TLX scale was taken after the completion of the second Flanker task and is composed of six subscales assessing subjective workload. The 32-item POMS scale was also assessed after completion of the second Flanker task and consists of five subscales; tension, depression, anger, fatigue and vigor. All items had to be scored from 0 (not at all) until 4 (extremely). The higher the score on a category, the more participants felt this mood state was present. The questionnaire was translated into the native language of the participants [Dutch [33]].

The subjects were given instructions to sleep for at least 7 h, refrain from the consumption of caffeine, alcohol and not to practice vigorous physical activity the day before each visit. In addition, to intra-individually standardize calorie- and macronutrient-intake, subjects were asked to have the same meal (in terms of content and quantity) the evening before each trial and not to have any food/drink intake but water after 22:00 the night before each trial. The use of any kind of medicinal products during and between the trials was prohibited. If subjects could not meet these standards they were excluded from the study. To facilitate the contact between the EEG-electrodes and the subjects' head, they were also asked to wash their hair (with neutral shampoo) the evening before the experiment.

5.3.3 EEG recordings and analysis

During the two Flanker tasks and the modified Stroop task, brain activity was continuously measured. Thirty two active Ag/AgCl electrodes were attached on the subjects' head (Acticap, Brain Products, Munich, Germany), according to the "10–20 International System" [24]. The sampling rate was set at 500 Hz (Brain Vision Recorder, Brain Products, Munich, Germany). Electrode impedance was kept <10 kΩ throughout the recording. Baseline measurements were taken 2 min with eyes open, 2 min with eyes closed. During EEG recordings, subjects were seated in a dim lit room, inserted earplugs and had been instructed to minimize movement of the head and eye blinking, to avoid frowning, to maintain the same posture and not to touch their head with their hands in order to minimize movement, sound and muscle artefacts.

Event-related potential (ERP) analysis The program Brain Vision Analyzer (version 2.1) was used to pre-process and process the data sets. Raw data were down-sampled to 256 Hz, filtered (high pass 0.1 Hz, low pass 45 Hz and Notch, Slope 48 dB/oct) with a Butterworth filter design and re-referenced to an average reference. For each data set of interest [i.e. ERP during the first, fourth and eighth block in the Stroop task] artefacts were semi-automatically removed. Then the different stimuli (Flanker task: incongruent; Stroop task: colour / meaning) were extracted from the EEG data sets. For stimulus locked ERP analysis, a data window was set at -200 to 800 ms relative to stimulus onset. Trials in which performance errors occurred were excluded. For each ERP epoch, independent component analysis (ICA) and inverse ICA further reduced artefacts. Furthermore, a baseline correction was applied (period -200 to 0 ms). Epochs were then averaged and the visually evoked potentials, P2, N2, P3b were assessed. Peak amplitudes and onset latencies were measured for the P2, N2 and P3b components in their specific region of interest (ROI; Table 1). The P2 is known to be frontally distributed [34] and was therefore analysed in the orbitofrontal cortex (OFC) and dorsolateral prefrontal cortex (DLPFC). It has been related to attentive stimulus evaluation or the recall of task rules [35]. The P2 was defined as the largest positive-going peak occurring within the time window between 80 and 260 ms and was visually confirmed. The N2 is usually interpreted as an index of conflict monitoring [36] and emerges fronto-centrally after the P2 [34], thus also for the N2 the OFC and DLPFC was analysed. The N2 was defined as the largest negative-going peak occurring within the time window between 180 and 440 ms and was visually confirmed. The P3b is linked to salience processing and appears to occur when subsequent attentional resource activations promote memory operations in temporal-parietal areas [37]. Therefore the fusiform gyrus (FFG), the angular gyrus (AG) and the somatosensory association cortex (SAC) were analysed to observe any effects on the P3b. The P3b was defined as the largest positive-going peak occurring within the time window between 180 and 415 ms and was visually confirmed. Thereafter, we exported the data from Brain Vision Analyzer to SPSS (version 22.0; SPSS, Chicago, IL) for further analysis.

Table 1. Regions Of Interest (ROI) defined by Brodmann Areas (BAs) and electrode sites according to the "10–20 International System". V denotes the ROI checked for that particular electroencephalography-measure.

Table 1. Regions Of Interest (ROI)

ROI	Brain region	BAs	Electrode sites	P2 & N2	P3b	EEG
1	Inferior/Orbitofrontal cortex	11, 47	F7	V	-	V
2	Broca's area	44, 45	FC6, F8	-	-	V
3	Dorsolateral prefrontal cortex	8, 9, 46	F3, Fz, F4	V	-	V
4	Anterior prefrontal cortex	10	FP1, FP2	-	-	V
5	Premotor cortex	6	FC1, FC2	-	-	V
6	Primary motor cortex	4	C3, Cz, C4	-	-	V
7	Somatosensory Association Cortex	7	Pz	-	V	V
8	Angular Gyrus	39	P3, P4	-	V	V
9	Fusiform Gyrus	37	P7, P8, PO9, PO10	-	V	V

Spectral power analysis Similar to the ERP analysis, the program Brain Vision Analyzer (version 2.1) was used to pre-process and process the data sets for the analysis of the total power. Raw data were down-sampled to 256 Hz, filtered (high pass 0.1 Hz, low pass 45 Hz and Notch, Slope 48 dB/oct) with a Butterworth filter design and re-referenced to an average reference. For each data set of interest [i.e. Continuous EEG measurements from the fifth to the eighth minute in the first (5-8 min), fourth (38 min 45 sec-41 min 45 sec) and eighth (83 min 45 sec-86 min 45 sec) block in the Stroop task] artefacts were semi-automatically removed. For each continuous EEG data set of interest segments with a length of 4 s and with an overlap of 2 s were extracted [38]. Subsequently ICA and inverse ICA further reduced artefacts. The resulting data segments were tapered with a Hanning window with 10% of the total segment length. Fast Fourier transform (FFT) power spectra with a spectral resolution of 0.25 Hz were calculated for both sides of the spectrum, resulting in FFT segments containing the full spectral information. The resulting FFT segments were averaged to stabilize the spectral content. The power in the FFT was extracted for theta (θ, 3.5–7.5 Hz), alpha (α1, 7.5–10 Hz; α2, 10–12.5 Hz) and beta (β1, 12.5–18 Hz; β2, 18–35 Hz) in each ROI.

5.3.4 Statistical analysis

All data are presented as means ± standard error (SE) unless stated otherwise. The Shapiro-Wilk test was used to test the normality of the data, sphericity was verified by the Mauchly's test. When the assumption of sphericity was not met, the significance of F-ratios were adjusted with the Greenhouse-Geisser procedure. *Subjective data.*

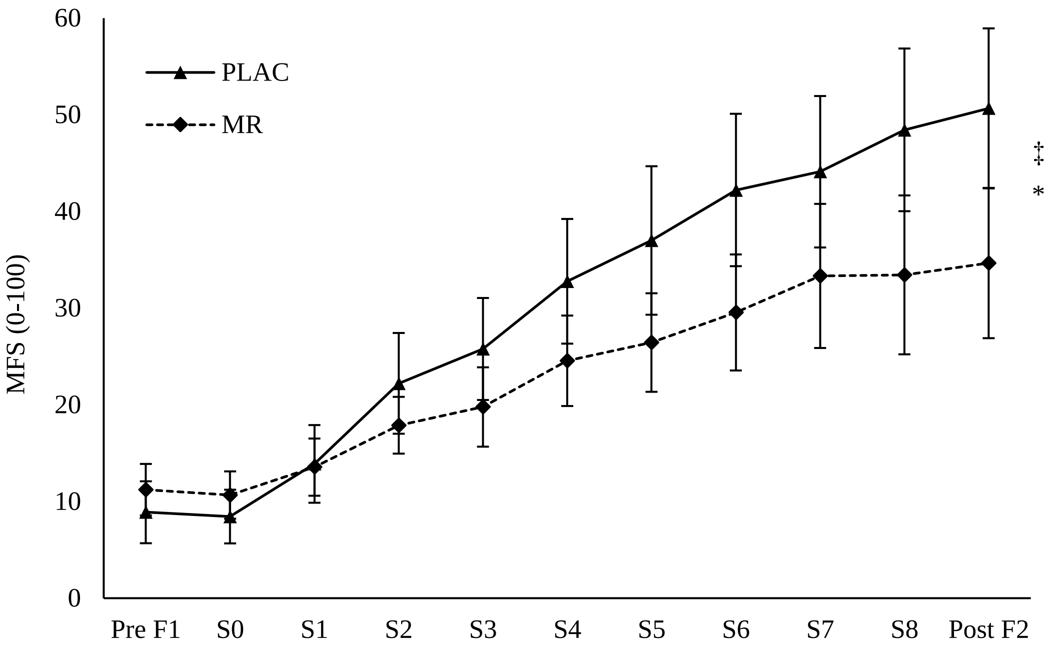
NASA-TLX-, SIMS- and POMS-data were not normally distributed and therefore Wilcoxon signed ranked tests were used to test the effect of condition (MR vs. PLAC) in each subscale. Paired sample t-tests were employed to assess the effect of condition on the pleasantness-rating of the taste stimuli. Two-way repeated measure ANOVAs were used to test for the effect of condition and time on motivation (2 x 10) and MFS (2 x 11). *Behavioural data*. Stroop accuracy-data had to be normalized to a baseline performance (i.e. performance on the first block = 100%) within each condition and subject (see Results) in order to be normally distributed. The effect of condition, time (second to eighth block in the Stroop) and stimuli (colour vs. meaning) on normalized Stroop accuracy-data was tested with a three-way repeated measures ANOVA (2 x 7 x 2). The same three-way repeated measures ANOVA with an extra level in the time variable (the first block; 2 x 8 x 2) was used to analyse Stroop RT-data. A two-way repeated measure ANOVA (2 x 2) was used to assess the effect of condition and time on Flanker-accuracy and -RT. *(Neuro)Physiological data*. The effect of condition and time on blood glucose concentration (2 x 2) and HR (2 x 11) was tested with a two-way repeated measure ANOVA. Four-way repeated measure ANOVAs were used to assess the effect of condition, time (first to eighth block in the Stroop), stimuli (colour vs. meaning) and ROI (see Table 1) on multiple ERP (P2-, N2- and P3b-amplitude and -latency). Square root transformed normalized (spectral power during baseline eyes open condition = 100%) spectral power ($\alpha 1$, $\alpha 2$ and θ) variables associated with mental fatigue were analysed with a three-way repeated measures ANOVA (condition, time and ROI; 2 x 3 x 9; see Table 1). If significant interaction effects in the repeated measure ANOVAs were observed, subsequent repeated measure ANOVAs or paired sample t-tests (depending on the amount of interacting factors) were performed in order to elucidate the main effect of the interacting factors. If no significant interaction effects were observed, main effects were immediately observed and further interpreted through pairwise comparisons with Bonferroni correction. Within-subjects correlation coefficients (r) were computed for the correlations between MFS/P2-amplitude in DLPFC and Stroop accuracy on 'meaning' stimuli/P2-amplitude in DLPFC using the method described by Bland and Altman [39]. This method adjusts for repeated observations within participants by using multiple regression with "participant" treated as a categorical factor using dummy variables. Significance was set at 0.05 for all analyses. All statistical tests were conducted using the Statistical Package for the Social Sciences, version 24 (SPSS Inc. Chicago, IL, USA).

5.4 Results

5.4.1 Subjective data

No significant condition x time interaction was found for self-reported mental fatigue. Self-reported mental fatigue significantly increased in time from 10.1 ± 2.5 before the first Flanker task to 42.7 ± 7.4 after the second Flanker task ($F(1.2, 9.3)=12.7$; $p=0.005$) and was, on average, significantly lower in MR (23.2 ± 4.4) compared to PLAC (30.4 ± 4.6; $F(1, 8)=9.0$; $p=0.017$; main effect of condition; Fig. 2). The POMS however showed no difference between conditions in fatigue or any other subscale (depression, tension, anger and vigor). No difference between conditions was observed in terms of general motivation towards the Stroop (assessed with the oral 0-100 scale) or intrinsic motivation, identified regulation, external regulation and amotivation (assessed with the SIMS). General motivation (assessed with the oral 0-100 scale) did decrease in time from 86.5 ± 2.9 at the start of the protocol to 69.9 ± 5.6 at the end of the Stroop task ($F(1.6, 14.8)=9.9$; $p=0.003$). The NASA-TLX data revealed that there was no effect of condition on any subscale (mental demand, physical demand, temporal demand, performance, effort, frustration). Although efforts were made to mask the differing taste between both mouth rinse solutions, participants scored the pleasantness of the bitter/sweet taste in MR (-0.9) significantly lower than in PLAC (0.7; p=0.008).

Fig. 2 Self-reported mental fatigue throughout the protocol; before and after the first Flanker task (Pre F1, S0), after each block during the Stroop task (S1, …, S8) and after the last Flanker task (Post F2). ‡ Significant effect of time (p<0,05). * Significant effect of condition (p<0,05). Data are presented as means ± SE.



5.4.2 Behavioural data

Stroop performance

A triple condition x time x stimulus-type interaction (F(6, 54)=2.7; p=0.022) for the normalized Stroop accuracy was found. A post hoc condition x time ANOVA in each stimulus-type revealed a condition x time interaction within the 'meaning' stimuli (F(6, 54)=3.3; p=0.008) and a main effect of time within the 'colour' stimuli (F(6, 54)=2.4; p=0.039; see Table 2). Concerning the 'meaning' stimuli, follow-up paired sample-t-tests within each time interval revealed that accuracy was higher in the eighth and last block of the Stroop in MR (100.4 ± 1.6%) compared to PLAC (91.0 ± 3.5%; p=0.032; see Table 2). Regarding Stroop RT, a time x stimulus-type interaction was observed in the three-way-ANOVA (F(7, 63)=8.1; p<0.001). The post-hoc condition x time ANOVA in each stimulus-type revealed that for the 'meaning' stimuli participants reacted faster in time (F(1.9, 17.1)=4.9; p=0.023; see Table 2) independent of condition. For the 'colour' stimuli no interaction or main effects were found.

Table 2 Stroop performance; Accuracy and RT in all eight blocks (11min15sec) of the Stroop task. Accuracy-data were normalized to the performance on the first block within each condition (=100%), data are presented as means ± SE; † indicates a trend towards a time-effect; ‡ indicates a significant time-effect; * indicates a significant difference compared to the analogous time interval in PLAC.

Table 2. Stroop performance; Accuracy and RT in all eight blocks (11min15sec) of the Stroop task

	Meaning stimuli								**Colour stimuli**							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
MR (accuracy ± SE; %)	100	97.3 ± 1.1	97.5 ± 2.3	97.7 ± 2.2	97.0 ± 1.3	98.9 ± 1.7	97.9 ± 1.8	100.4 ± 1.6*	100	99.0 ± 0.6	98.9 ± 1.0	97.3 ± 0.9	98.1 ± 1.5	97.4 ± 1.2	96.7 ± 1.4	97.3 ± 1.7‡
PLAC (accuracy ± SE; %)	100	98.6 ± 1.9	98.6 ± 1.8	98.1 ± 2.0	95.4 ± 2.6	93.0 ± 3.1	96.2 ± 2.9	91.0 ± 3.5†	100	96.8 ± 1.0	96.7 ± 1.2	95.6 ± 2.4	94.7 ± 3.1	93.9 ± 2.6	93.6 ± 2.5	92.5 ± 3.1‡
MR (RT ± SE; ms)	642 ± 12	609 ± 10	603 ± 9	595 ± 13	601 ± 12	603 ± 15	598 ± 12	604 ± 17‡	557 ± 10	559 ± 10	563 ± 11	551 ± 10	560 ± 14	550 ± 12	559 ± 12	561 ± 13
PLAC (RT ± SE; ms)	638 ± 8	604 ± 4	613 ± 10	606 ± 9	613 ± 12	615 ± 13	603 ± 11	609 ± 11‡	553 ± 8	557 ± 11	566 ± 11	564 ± 11	571 ± 16	564 ± 13	566 ± 15	565 ± 14

Flanker performance

No interaction effect or time effect was observed for accuracy, participants performed worse in PLAC (0.89 ± 0.02) than in MR (0.91 ± 0.01; F(1, 9)=6.6; p=0.031; see Table 3). Regarding RT no interaction effect or main effect of condition or time was observed (see Table 3).

Table 3. Flanker performance; Accuracy and RT in pre and post Flanker task. Data are presented as means ± SE; * indicates a significant difference compared to PLAC.

Table 3. Flanker performance; Accuracy and RT in pre and post Flanker task

	Pre	**Post**
*MR (accuracy ± SE)**	0.91 ± 0.02	0.91 ± 0.01
PLAC (accuracy ± SE)	0.92 ± 0.01	0.86 ± 0.03
MR (RT ± SE; ms)	350 ± 13	342 ± 11
PLAC (RT ± SE; ms)	360 ± 8	365 ± 11

5.4.3 (Neuro)Physiological data

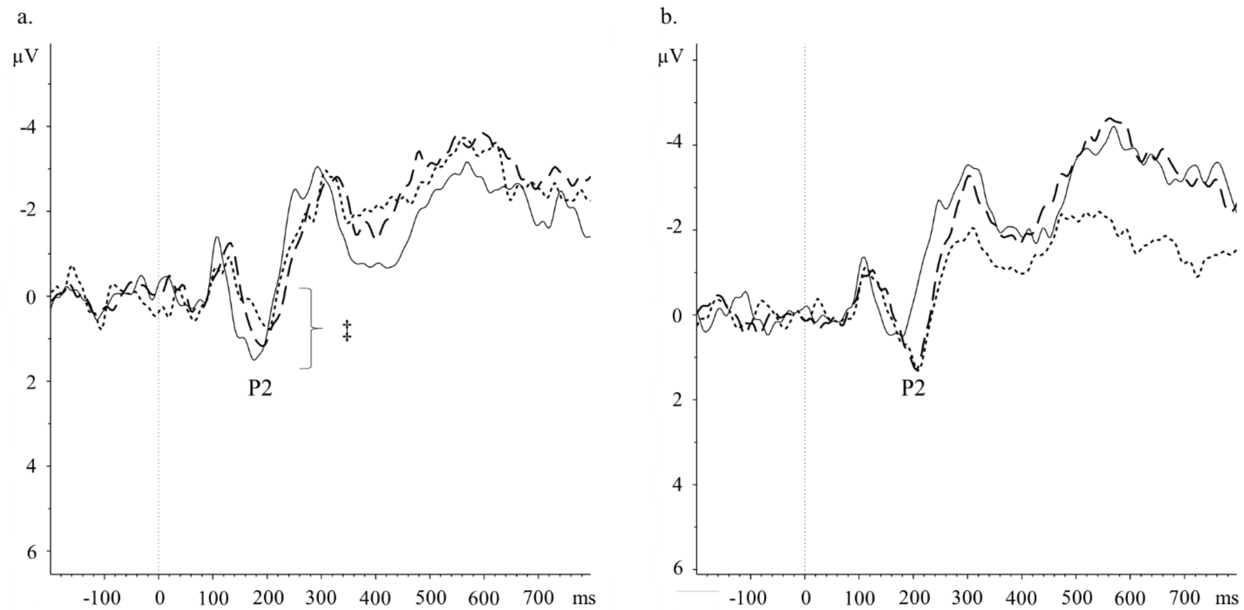
Heart rate and blood glucose

For HR no interaction effect or main effect of condition was observed. HR did however decrease in time in both conditions (F(4.1, 37.0)=5.0; p=0.002) from 71 ± 3 bpm before the pre-Flanker to 63 ± 3 bpm after the post-Flanker. For blood glucose no interaction effect or main effect of time was found. There was however a main effect of condition (F(1, 8)=21.6; p=0.002). Blood glucose was higher in MR (95.9 ± 3.9 mg/dl) than in PLAC (88.4 ± 3.2 mg/dl).

Event related potentials

P2. For P2-amplitude a condition x stimulus-type x ROI (F(1, 9)=5.3; p=0.046) and time x stimulus-type x ROI (F(2, 18)=4.3; p=0.03) interaction effect in the four-way ANOVA led towards the implementation of a post hoc condition x time x ROI ANOVA in each stimulus type. This revealed a condition x ROI interaction (F(1, 9)=5.8; p=0.039) for the 'meaning' stimuli and a condition x time interaction (F(2, 18)=5.0; p=0.018) for the 'colour' stimuli. Subsequently, for the 'meaning' stimuli, follow-up condition x time ANOVAs in both ROIs were performed. For the 'colour' stimuli condition x ROI and time x ROI ANOVAs were performed. Within the 'meaning' stimuli, the P2-amplitude in the OFC was larger in MR (2.6 ± 0.5 µV) than in PLAC (1.9 ± 0.4 µV; F(1, 9)=9.9; p=0.012) independently from time. In the DLPFC a condition x time interaction was present (F(2, 18)=4.2; p=0.032). Amplitude decreased in time in PLAC (F(2, 18)=5.1; p=0.017; see Fig. 3a), whilst in MR time did not have an effect (Fig. 3b). Paired sample-t-tests indicated that P2-amplitude was larger in PLAC in the first time-interval (p=0.049; see Fig. 3a & b), while in the third and last time-interval it was larger in MR (p=0.034; see Fig. 3a & b). Within the 'colour' stimuli, P2-amplitude decreased over time in PLAC (F(2, 18)=11.1; p=0.001) independently from ROI. In MR P2-amplitude did not differ over time (no time x ROI interaction or main effect of time) in the ‘colour’ stimuli. No interaction effects or main effect of time or condition were observed for latency. *N2.* For N2-amplitude no interaction effects or main effect of time or condition were observed. For N2-latency a time x stimulus-type interaction was present (F(2, 18)=6.4; p=0.008). N2-latency on the ‘meaning’ stimuli became longer in time (304.2 ± 12.0 ms → 330.8 ± 19.9 ms) independent of condition (F(2, 18)=4.3; p=0.029). On the ‘colour’ stimuli, N2-latency did not differ between conditions or in time. *P3b.* No interaction effects or main effect of time or condition were observed for P3b-amplitude. A time x ROI interaction was present in the four-way ANOVA for P3b-latency. Subsequent follow up condition x time x stimulus-type ANOVAs in all three ROIs revealed that only in the FFG, P3b-latency became longer in time (261.9 ± 11.8 ms → 293.0 ± 8.5 ms; F(2, 18)=11.6; p=0.001) independent of condition.

Fig. 3 a. Grand-average ERPs at Fz elicited by the ‘meaning’ stimuli (i.e. indicate the meaning of the word) in the first block (solid black line), fourth block (large dashed line) and eighth block (small dashed line) during the Stroop task in PLAC. ‡ Significant main effect of time (p<0.05). **b.** Grand-average ERPs at Fz elicited by the ‘meaning’ stimuli in the first block (solid black line), fourth block (large dashed line) and eighth block (small dashed line) during the Stroop task in MR.



Spectral power

In all spectral power frequencies (θ, α1, α2, β1 and β2) no interaction or main effect of condition and time was observed. Only β1-power was found to decrease in time during the Stroop task (F(2, 18)=5.6; p=0.013).

5.4.4 Correlations

Within-subjects correlation coefficients were computed for those parameters that, similar to the markers of mental fatigue, were affected by the intervention (i.e. an increase in self-reported mental fatigue and a decrease in accuracy). No significant correlations were however observed between P2-amplitude and MFS or Stroop accuracy on the ‘meaning’ stimuli.

5.5 Discussion

This study is the first to assess the ability of serial CAF-MALT mouth rinsing to counteract mental fatigue. It was observed that a serial CAF-MALT mouth rinse-intervention counteracts subjective, behavioural and electrophysiological (i.e. decreased P2-amplitude was counteracted in MR) mental fatigue.

In both conditions, MR as well as PLAC, the 90-min Stroop task elicited mental fatigue. This was measured as an increase in self-reported mental fatigue and a decrease in accuracy. However, small but important differences were observed between both conditions. Despite that self-reported mental fatigue significantly increased in both conditions, significantly less mental fatigue was perceived in MR. Participants commenced the protocol in both conditions with a similar degree of self-reported mental fatigue (MR: 11.2 ± 2.7; PLAC: 8.9 ± 3.2), whilst at the end this differed substantially (MR: 34.7 ± 7.8; PLAC: 50.7 ± 8.3). POMS measures however showed no difference in fatigue between conditions. It was suggested by Van Cutsem et al. [3] that the POMS may be less capable of detecting small but relevant short-term changes in mental fatigue and this seems to be confirmed in the present study.

Behaviourally, performance on the 'meaning' stimuli (which represent the stimuli in which subjects had to respond to the meaning of the word, and not the colour), also indicated a difference was present between conditions. This became specifically apparent in the eighth and last block of the Stroop task. Accuracy on the 'meaning' stimuli in this block was higher in MR compared to PLAC. This means that participants were able to keep up their cognitive performance for longer. Furthermore participants reacted faster on the 'meaning' stimuli in time, independent from the condition. This indicates participants adopted the higher risk strategy with increasing time-on-task with more success in MR than in PLAC, as participants were only able to keep up accuracy in MR condition. The lower occurrence rate (25% of all stimuli) of these 'meaning' stimuli brings along a higher mental demand, which could explain why performance on these stimuli was more sensitive to the intervention-effect. In order to be able to observe the effect of mental fatigue on cognitive performance independently from time-on-task, a Flanker task was completed before and after the mentally fatiguing task. Performance on this task confirmed that cognitive performance was better in MR, mainly due to a higher accuracy on the Flanker task completed after the mentally fatiguing task (see Table 3). Consequently also this measure indicates that participants were more resistant to mental fatigue in MR.

Multiple functional magnetic resonance imaging- [30, 40, 41] and EEG-studies [42] have demonstrated that rinsing a solution containing glucose and/or caffeine activates certain brain regions (e.g. anterior cingulate cortex, orbitofrontal cortex, striatum, …). An objective effect of CAF-MALT mouth rinsing on the brain was confirmed by our data. Specifically, serial CAF-MALT mouth rinsing prevented the decrease in P2-amplitude in time. The P2 is a component of an ERP that appears around 200 ms after the onset of a stimulus [34] and its amplitude is suggested to serve as an electrophysiological marker of the process in which cue information is associated to the functional properties of this information (i.e. the recall of task rules) [34, 43]. In other words, serial CAF-MALT mouth rinsing prevented a decrease in the ability to select relevant cue information. Nonetheless, the change in P2-amplitude was not significantly correlated with the other markers of mental fatigue. In contrast, the frequently reported shift of EEG power towards low-frequency bands (δ, θ, α) in mentally fatigued subjects [38, 44-48] was not observed in the present study. It is possible this shift in spectral distribution was prevented in both MR and PLAC by the brain activating properties of both substances. In the study of Chambers et al. [30] it is shown that caloric (e.g. the solution used in MR in the present study) as well as non-caloric sweetened (e.g. the solution used in PLAC in the present study) solutions activate multiple brain areas (i.e. right insula, frontal operculum, left dorsolateral prefrontal cortex). The present results suggest that a prevention of this shift in spectral distribution [i.e. a decrease in arousal [49]] is however not sufficient to postpone the occurrence of mental fatigue, subjectively and behaviourally. Unfortunately we did not include a control trial (i.e. without mouth rinse) to confirm whether the spectral distribution-shift occurred in the first place in the present study. Therefore we can also not further substantiate this suggestion.

A potential mechanism for the serial CAF-MALT mouth rinsing positively affecting mental fatigue might be the absorption through the oral mucosa, especially for a lipophilic agent like caffeine [50]. Caffeine, rapidly taken up in the bloodstream through the buccal mucosa, may arrive in the brain via the systemic circulation and exert its' known effects (i.e. antagonist of adenosine). Doering et al. [51] investigated however the effects of serial caffeine mouth rinsing on endurance cycling time-trial performance and found no significant increase in plasma caffeine concentration after repeated oral exposure. Similarly, Rollo et al. [52] assessed whether peripheral blood glucose concentration is affected by serial carbohydrate mouth rinsing (i.e. Lucozade Sport, Brentford, England) and did not observe any increase. This is confirmed by our results, although blood glucose was higher in MR, it was not altered differently in time in both conditions. In addition, the time dynamics of the changes in other parameters like P2-amplitude and accuracy during the Stroop task cannot be explained by the higher blood glucose in MR. Therefore this difference in glucose between MR and PLAC, most probably, does not explain our results. Although both caffeine and maltodextrin were probably not taken up systemically during the serial CAF-MALT mouth rinsing, it could still be that minimal amounts of both substances were absorbed through the oral mucosa and exerted their effect in the brain without showing up in the blood. A placebo effect [53] could also explain the observed results and could have been triggered by the participants' awareness that they were expected to perform better in one trial compared to the other. Participants were however informed in a way that they were naïve of the study's real aims and hypotheses. This also anticipated the fact that pleasantness of taste was rated lower in MR than in PLAC. A possible role of motivation in the observed results was also accounted for. A monetary incentive was provided in an attempt to prevent task disengagement and to restrict possible alterations in motivation throughout the task performance [3, 54]. In addition the level of motivation was monitored before the start of the task (SIMS) and during the task (oral 0-100 scale). In none of the two methods an effect of the intervention was found. A final potential mechanism by which the serial CAF-MALT mouth rinsing attenuated mental fatigue is the activation of specific brain regions (i.e. the anterior cingulate cortex and the right caudate, that forms part of the striatum) known to produce dopamine [30, 55]. A mechanism that has already been suggested in the self-control literature, where a carbohydrate-mouth rinse has been shown to successfully counter on self-control impairments [56]. Moreover mental fatigue has already been associated multiple times with alterations in the anterior cingulate cortex [4, 6, 57, 58]. This way a mouth rinse containing caffeine and maltodextrin might be able to (partly) restore dopaminergic transmission in the striatum and anterior cingulate cortex and postpone mental fatigue by activating sensory neurons in the mouth and initiating a signal transduction cascade towards the brain.

Future research

In the present study caffeine and maltodextrin were combined in one mouth rinse in order to increase the chances to successfully counter the electrophysiological changes associated with mental fatigue. This assumption was based on a study conducted by Beaven et al. [22], who found that there was an additive effect of combining caffeine and carbohydrates on power production during repeated sprints on a cycle ergometer. The additive positive effect suggested that distinct mechanisms are involved in the performance enhancement [22]. This indicates that it would be interesting to look at the separate effects of a maltodextrin mouth rinse and a caffeine mouth rinse on the occurrence of mental fatigue. Looking at the separate effects of both mouth rinses might further increase our knowledge on the electrophysiological measures laying at the base of the occurrence of mental fatigue. The present study was completed with low caffeine users in a fasted state, meaning that it is still to be confirmed whether these effects would still occur in another population at another time of day and when switching between tasks. Another important aspect that needs further investigation is whether serial mouth rinsing is also capable of postponing mental fatigue in a less demanding way. The mouth rinse intervention in the present study was based on a study of Carter et al. [59], were participants also had to rinse their mouth every 12.5% task completion. A less demanding mouth rinse-protocol, that is still able to postpone mental fatigue, would greatly improve its applicability. Caution is however warranted as a recent study of Kumar et al. [60] reported that a single carbohydrate mouth rinse preceding a 20-min cognitive task, was unable to prevent a decrease in cognitive performance in time.

5.6 Conclusion

A 90-min Stroop task induced mental fatigue in both MR and PLAC. However in the MR condition mental fatigue was induced to a lesser extent, indicated by a slower increase in self-reported mental fatigue, the ability to keep up cognitive performance and by preventing a mental fatigue-associated electrophysiological change (i.e. decreasing P2-amplitude) occurring with increasing time-on-task. Two potential mechanisms to account for the ability of serial CAF-MALT mouth rinsing to counter mental fatigue are: 1) absorption of caffeine and maltodextrin via the brain that does not show up systemically; 2) restored dopaminergic brain transmission via sensory neurons initiating a signal transduction cascade towards the brain. In addition, for individuals that do not want to or cannot ingest caffeine and/or carbohydrates but need to reduce mental fatigue, these findings provide a possible practical solution.

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Chapter 6: General discussion & conclusion

6.1 Main findings

- Mental fatigue and physical performance; literature review (Chapter 2)
    - **Research Question 1:** Does mental fatigue affect physical performance, and if yes, what are the underlying factors?

Mental fatigue impairs endurance performance (decreased time to exhaustion and self-selected power output/velocity or increased completion time), **and this impairment appears to be associated with a higher than normal perceived exertion.** Physiological variables traditionally associated with endurance performance (heart rate (HR), blood lactate ([Bla]), oxygen uptake (VO_2), cardiac output (CO)) were not directly affected by mental fatigue during and after endurance performance. Maximal strength, power, and anaerobic work were not affected by mental fatigue. This led to the conclusion that duration, intensity and a cognitive component in the physical task appear to be important factors in the decrease in physical performance due to mental fatigue.

- Mental fatigue and the heat-induced decrease in endurance performance (Chapter 3)
    - **Research Question 2:** Does mental fatigue affect endurance performance in the heat?

Mental fatigue does not impair endurance performance in the heat. Although a 'mild form' of mental fatigue was successfully induced in the heat (30°C) with a 45-min Stroop task, this mild mental fatigue did not influence participants' psychological or physiological responses during the endurance task or their endurance performance in the heat. These findings could indicate that heat is a moderating factor of the mental fatigue-induced endurance impairment. It is plausible the higher perception of effort experienced during endurance exercise in a hot environment or when mentally fatigued may share a common psychobiological mechanisms: negative valence. Exercising in the heat is associated with subjective thermal strain (e.g. thermal discomfort), whereas mental fatigue is known to induce a more negative mood. The valence of emotional stimuli has been shown to affect perception of effort [1] and the activity of the cingulate cortex [2] and prefrontal and premotor cortical areas [3] related to perception of effort [4, 5]. Thus, it is plausible that a similar psychobiological mechanism may explain the effects of heat stress and mental fatigue on perception of effort and why the effects of the two stressors do not summate. In other words, in conditions of thermal discomfort, mild mental fatigue may not lead to a further increase in negative valence and perception of effort.

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    - **Research Question 3:** Does a heat pad, locally applied to the upper back, impair endurance performance?

Subjective thermal strain impairs endurance performance in a temperate environment. This finding substantiates that subjective thermal strain is a mediator of the heat-induced performance impairment, independently from the physiological strain that is associated with it. Furthermore, it substantiates the hypothesis that heat stress and mental fatigue may share a common psychobiological mechanism, i.e. the negative valence of emotions associated with both heat stress and mental fatigue increases perception of effort and subsequently impair physical performance. Neurophysiologically, this might be explained by a higher activity of the premotor cortex when exercising in an unpleasant condition like when enduring very high thermal discomfort. This suggestion is supported by a neuroimaging study showing higher premotor cortex activity when unpleasant stimuli are provided during exercise [3]. Furthermore the activity of premotor and/or motor areas of the cortex is associated with RPE during exercise [5-7] as predicted by the corollary discharge model of perceived effort [8]. From a more applied point of view these results justify the use of specific techniques aiming to reduce subjective thermal strain (e.g. menthol spray).

- Mental fatigue and sport-specific psychomotor performance (Chapter 4)
    - **Research Question 4:** Does mental fatigue impair sport-specific psychomotor performance?
    - **Research Question 5:** Does level of training affect the impact of mental fatigue on sport-specific psychomotor performance?

Mental fatigue decreased open skill-visuomotor performance in controls as well as badminton players. These results substantiate that mental fatigue does not only impair endurance sports, but also impairs sport-specific psychomotor performance (e.g. open skill-visuomotor performance). Mental fatigue particularly impaired the response time to the complex stimuli, rather than the simpler stimuli in both the badminton players and the controls. This is in accordance with previous studies on the effect of mental fatigue on cognitive performance [9-11], showing that executive control (i.e. the control to overrule an automatic response) is compromised by mental fatigue, but more automatic cognitive processing is relatively insensitive to this state. In addition, these results also demonstrate that, although Martin et al. [12] indicated that superior inhibitory control might be a psychobiological characteristic of athletes, this does not mean they are immune to mental fatigue.

- Counteracting mental fatigue (Chapter 5)
    - **Research Question 6:** Does serial caffeine-maltodextrin (CAF-MALT) mouth rinsing counteract mental fatigue?

Serial CAF-MALT mouth rinsing counteracts subjective, behavioural, and electrophysiological mental fatigue. Practically this intervention provides the opportunity to avoid the, sometimes, unwanted side effects of caffeine and/or maltodextrin intake. Caffeine intake, for example, can cause tremors, nausea, nervousness, increased levels of anxiety, or gastrointestinal distress [13]. In addition, it may also adversely affect sleep patterns [13]. Ingesting carbohydrates might also be forbidden (e.g. during Ramadan) or unwanted for health reasons (e.g. diabetes and obesity), especially in the form of energy drinks [14]. Mechanistically two potential pathways can be put forward to account for the ability of serial CAF-MALT mouth rinsing to counter mental fatigue: (1) absorption of caffeine and maltodextrin via the oral mucosa that does not show up systemically and (2) restored dopaminergic brain transmission via sensory neurons initiating a signal transduction cascade towards the brain.

6.2 State of the art of mental fatigue-research in sports science

To situate the results obtained in the present PhD within the existing body of research on mental fatigue in sports science and to provide an overview of the advances made in the mental fatigue-research in sports science we decided to replicate the search-strategy defined in our published systematic review on mental fatigue and physical performance. This replication resulted in an oversight of the published studies on mental fatigue and physical performance between April 2016 and December 2018. The search in Pubmed and Web of Science indicated that within this period, besides the studies included in the present PhD, seven more articles were published on the topic [15-21]. Screening the reference lists of these seven articles resulted in 12 more articles on the topic of mental fatigue and physical performance [22-33].

6.2.1 Methodology to induce mental fatigue

In our systematic review the importance of the length of the cognitive task used to induce mental fatigue was already indicated and substantiated [34]. A cut-off point at 30-min was set based on the reasoning that shorter tasks may be sufficiently arduous, yet they may not be of sufficient duration or intensity to result in mental fatigue. Despite that we still support the reasoning behind this cut-off point at 30-min, we are aware that applying this cut-off results in the exclusion of multiple high quality studies. These studies would otherwise have provided valuable additional knowledge and as such conducting a meta-analyses that includes all studies that assessed the effect of a preceding cognitive task on physical performance is of great importance. Such a meta-analyses could result in bringing together both the line of research on self-control depletion and on mental fatigue. However, in the following discussion on the 19 articles that were published in the last 2.5 years on mental fatigue and physical performance, it was decided, similarly as in Chapter 2, to apply the cut-off of 30-min. This resulted in the exclusion of five articles [15, 21, 22, 26, 27]. Despite relevant attempts in inducing mental fatigue in a more ecological valid way [27], assessing the effects of prior cognitive exertion on applied open-skill sports performance [21] and assessing the role of self-efficacy in the negative effects of mental fatigue on physical performance [22], the results of these studies will not be further included in the provided state of the art of the mental fatigue-research in sports science. This results in 14 new studies on the topic. When these 14 new studies are compared with the studies included in the systematic review [34], it is clear that there is a tendency towards the use of a 30-min Stroop task to induce mental fatigue. Six out of 14 used such a 30-min Stroop task [16, 17, 19, 24, 28, 32]. In contrast, Pires et al. [23] chose for a 30-min rapid visual information processing test, in the two studies of Head et al. [29, 30] a 50-min Go/No-Go task was employed, while Vrijkotte et al. [25] went for a 90-min Stroop task, Silva-Cavalcante et al. [18], Azevedo et al. [31] and Le Mansec et al. [20] for a 90-min AX-CPT and Otani et al. [33] for a 90-min test battery consisting of the Stroop task, Sternberg paradigm and Rapid visual information processing test. Within this PhD the choice was made to employ the Stroop task to induce mental fatigue, however unlike the majority of the other recently published studies, a 45-min (see Chapter 3) and a 90-min Stroop task was used (see Chapter 4 & 5). As previously indicated the length of the task used to induce mental fatigue is important as it is assumed that the longer the task lasts the more mental fatigue is induced [35]. Looking at our own studies that induced mental fatigue and assessed its effect on physical performance it seems this statement is substantiated. In Chapter 3 (part 1) subjective mental fatigue was scored ~56/100 after a 45-min Stroop task, while in Chapter 4 this was scored ~68/100 after a 90-min Stroop task. The tendency towards using 30-min versions of cognitive tasks to induce mental fatigue is probably triggered by such designs being less time-demanding, but caution is warranted due to the uncertainty of being able to induce sufficient mental fatigue with such shorter tasks. Another point of attention is the control task, the majority of the studies published before and after April 2016, including our own studies, used a documentary, reading magazines or seated rest as a control condition. Despite the obvious assumption that these tasks are less/not mentally fatiguing, this might not be the case. Both in Chapter 3 and 4, watching documentaries was observed to induce a significant amount of subjective mental fatigue. This subjective mental fatigue induced by the documentaries was still lower than the fatigue induced by the Stroop task, but calls for attention in the design of future studies on the topic. Mental fatigue arising from watching documentaries might result from the false assumption that the chosen documentaries are engaging, consequently the self-control needed to stick with watching aversive documentaries enlarges the probability of these documentaries inducing mental fatigue. Attention is thus required in future studies to select appropriate control tasks that maximize the ability to observe the effects of mental fatigue on physical performance.

In our systematic review (see Chapter 2) we indicated that to confirm whether mental fatigue was induced requires subjective, behavioural, and physiological measures, and the interactions between all three manifestation areas of mental fatigue should be interpreted. In the systematic review, most studies that were included assessed at least two of these manifestation areas in order to control whether mental fatigue was induced [36-39]. In the recently published research on mental fatigue and physical performance (i.e. after April 2016), this suggestion is mostly not taken into account. Eight out of the 14 new studies solely included a subjective measure as manipulation check [16-20, 31-33], despite all of them had the opportunity to assess and report performance (in function of time-on-task) on the mentally fatiguing task. Even better than reporting the time-on-task evolution of performance on the mentally fatiguing task would have been to include an independent measure of cognitive performance (i.e. the indirect method [34]), however only one study did this [24]. Slimani et al. [24] used the d2-test as independent measure of cognitive performance and observed performance on this test was impaired after the mentally fatiguing task compared to after the control task. Besides subjective and behavioural markers of mental fatigue, neurophysiological manipulation checks were also suggested in our review [34]. However, only the two studies of Head et al. [29, 30] and the study of Pires et al. [23] attempted to substantiate (neuro)physiologically whether mental fatigue was successfully induced. In their first study Head et al. [29] found that VO_2 did not differ while completing the mentally fatiguing task and the control task. In their second [30] they reported that heart rate variability was lower during the mentally fatiguing task than the control task. Pires et al. [23] monitored prefrontal brain activity and observed that, similarly like our own results in Chapter 3, θ-power at the FP1-position was higher during the mentally fatiguing task compared to the control task and more importantly that θ-power increased as the rapid visual information processing-task progressed. This analysis of the employed manipulation checks exposes the need for future studies to adopt a more thorough strategy. In our own studies (see Chapter 3 and 4) we attempted to apply such a strategy and monitored different subjective, behavioural and (neuro)physiological markers of mental fatigue, which resulted in a more nuanced view on the mental fatigue that was induced.

6.2.2 Behavioural effects of mental fatigue

On a behavioural level, it was concluded in our systematic review that particularly endurance performance appeared to be impaired by mental fatigue [36, 38, 40-42]. In Chapter 3 (part 1) however, we did not succeed in replicating this negative effect of mental fatigue on endurance performance in a different environment (i.e. the heat). Multiple reasons are put forward that could possibly account for this observation, yet further research is necessary in order to pinpoint the actual reason. In the meantime, other studies also attempted to substantiate the statement that mental fatigue impairs endurance performance [16-18, 23-25, 29, 31-33]. Seven of the 10 studies were able to confirm this, some examples are: (1) Salam et al. [17] found that time-to-exhaustion (TTE) was reduced by an average of ~15% across exercise intensities equivalent to Δ40, Δ60, Δ80, and 100% VO_{2peak}, (2) Penna et al. [16] observed a ∼1.2% increase in time to complete a 1500-m swim time trial (TT), (3) Pires et al. [23] reported that the time to complete a 20-km time trial was ∼2.7% slower when mentally fatigued, and (4) Slimani et al. [24] observed a decreased performance (i.e. a lower attained maximal running speed; ∼8.2%) on the 20-m multistage fitness test (i.e. an incremental shuttle run test) due to mental fatigue. In contrast, Silva-Cavalcante et al. [18] found no effect of mental fatigue on time to complete a 4-km cycling TT, Vrijkotte et al. [25] did not observe any difference in the maximal wattage reached in two consecutive incremental cycling tests due to mental fatigue and Head et al. [29] showed that the amount of muscle resistance exercise repetitions was also not altered by mental fatigue. Taking all behavioural findings into account, the effect of mental fatigue on endurance performance is thus mostly replicated, yet not consistently. Possible moderating factors of the effects of mental fatigue on endurance performance could be cognitive load of the physical performance (e.g. little/no pacing required [18, 25]) and preceding physical activity prior physical performance (e.g. preloaded TT in the study of Van Cutsem et al. [43]). Another moderating factor could be heat, in our own mental fatigue-study in the heat [43] it appeared to overrule the mental fatigue-induced performance-impairment. However, others demonstrated that the negative effect of heat might also work synergistically with mental fatigue to further decrease endurance performance [33]. This is not the first fatigue-related line of research where heat has been found to act as a moderating variable [44] and calls for further research to explore the role of heat in the effects of mental fatigue.

Besides an endurance component, a cognitive component also seemed to play a role in observing a negative effect of mental fatigue on physical performance (See Chapter 1). In sports, a cognitive component can be recognized in team sport players making an immeasurable amount of high-risk and high-pressure decisions within a game, or in the particular stimulus-response situation (i.e. anticipating the opponent) in one-on-one games (e.g. fencing, badminton). In the published systematic review two studies were cited that already gave a first impression on the effect of mental fatigue on sport-specific psychomotor performance [42, 45]. Smith et al. [42] used the Loughborough Soccer Passing and Shooting Test with experienced soccer players and found that their shot speed and accuracy decreased when mentally fatigued. Badin et al. [45] observed that mental fatigue impaired most technical variables (e.g. pass accuracy and tackle success) in soccer players during a Small-Sided-Game (SSG). In a follow-up study Smith et al. [46] also assessed soccer-specific decision-making skills and reported that accuracy and response time were impaired by mental fatigue and that this was not mediated by altered visual search behaviour. The results in the present PhD substantiate that mental fatigue, in addition to endurance performance, negatively affects sport-specific psychomotor performance. In Chapter 4 it was observed that mental fatigue deteriorates badminton-specific psychomotor performance in trained athletes and untrained controls. From the 14 articles that were gathered by replicating our search from the systematic review, five studies [19, 20, 28, 30, 32] also provide some further insight in the effect of mental fatigue on psychomotor skills. Coutinho et al. [19] and Moreira et al. [28] both assessed the effect of mental fatigue on tactical/technical behaviour in a SSG in respectively a soccer and a basketball setting, while Le Mansec et al. [20], Head et al. [30] and Veness et al. [32] evaluated respectively the possible impairments in table tennis, marksmanship and cricket performance when mentally fatigued. All five studies reported reductions in performance due to mental fatigue. For example, in the study of Coutinho et al. [19] mental fatigue resulted in a likely ~8% decrease in the time that players spent synchronized in the longitudinal displacements, while in the study of Moreira et al. [28] mental fatigue was associated with an increased total number of turnovers (i.e. when a team loses possession of the ball to the opposing team before a player takes a shot at their team's basket) and Le Mansec et al. [20] found that ball speed decreased and number of faults increased in mentally fatigued participants, resulting in a lower overall table tennis performance. Together with our results from Chapter 4 this demonstrates mental fatigue negatively impacts sport-specific psychomotor performance and substantiates the necessity to further investigate this phenomenon.

6.2.3 Physiological effects of mental fatigue

Except for the study of Pires et al. [23], the seven studies that successfully replicated the impairment in endurance performance due to mental fatigue all monitored rather basic physiological measures during physical performance (e.g. HR, heart rate variability (HRV), [Bla], VO_2, electromyography (EMG), sweat rate). It appears that the focus was to provide further insight on the behavioural/performance effects of mental fatigue rather than to specifically design a study to increase our knowledge on the possible mechanisms behind these behavioural/performance effects. As such, besides confirming the statement that mental fatigue does not reduce endurance performance by altering physiological, cardiorespiratory, and neuromuscular responses to the subsequent exercise [34], extra information on the possible mechanisms mediating the mental fatigue-induced impairment in endurance performance is scarce. Slimani et al. [24] did not follow up any physiological measure during endurance performance, Salam et al. [17] found no effect of mental fatigue on HR but did find an effect on [Bla], Penna et al. [16] did not observe any change in HRV due to mental fatigue and Azevedo et al. [31] confirmed the results of Pageaux et al. [47] that mental fatigue does not affect EMG during physical performance. Pires et al. [23] is the only study that went one step further and measured a less straightforward physiological measure during endurance performance. They assessed prefrontal brain activity during the 20-km TT and observed that θ-activity was increased when mentally fatigued. Brain activity in this study [23] is however only measured at the FP1 position, this inevitably limits artefact-rejection possibilities and does not provide a window on the entire brains' activity. Despite this disadvantage it is only the second study - after the study of Brownsberger et al. [40] - to provide further insight in the prefrontal cortex activation during an endurance performance in a mentally fatigued state. Pires et al. [23] correctly point out that the increased θ-activity in mentally fatigued cyclists could reflect their lower ability to preserve adequate inhibitory control and attentional location during exercise.

Our own study (see Chapter 4), as well as all other five studies that assessed the effect of mental fatigue on sport-specific psychomotor performance, unanimously point out that mental fatigue negatively affects this type of performance. Consequently, these studies provide excellent insights on the behavioural level. In contrast, still a lot must be elucidated mechanistically. Only the studies of Badin et al. [45] and Moreira et al. [28] attempted to provide some further insight in possible physiological mediators of the mental fatigue-induced impairment in sport-specific psychomotor performance. Badin et al. [45] measured HR but did not find any conclusive evidence on a possible effect of mental fatigue. Moreira et al. [28] measured HR and salivary parameters in response to the physical performance, but subsequently employed a magnitude-based inferential statistical approach resulting in a difficult interpretation of the gathered data. One possible explanation for the current scarcity of studies assessing physiological mediators of the mental fatigue-induced decrease in sport-specific psychomotor performance is the complexity in objectively measuring sport-specific psychomotor performance. The challenge of measuring performance is relatively straightforward in situations where there is a clear and measurable performance outcome (e.g. cycling, swimming). However, effectively capturing performance in sport-specific psychomotor tasks is far more complex since it is based on several inter-related component skills (e.g. perceptual, cognitive and motor). These skills may be harder to isolate under controlled and reproducible settings, and performance decrements in these skills may even be harder to associate with (neuro)physiological alterations. Nonetheless, in order to advance this field of research, future studies should consider monitoring possible (neuro)physiological mediators.

6.2.4 Psychological effects of mental fatigue

Based on the psychobiological model [48] motivation and perceived exertion or the two most often monitored psychological constructs in this line of research. Five of the 10 new studies (i.e. after April 2016) on mental fatigue and endurance performance assessed motivation to perform on the physical task. Only in the study of Pires et al. [23] an effect of mental fatigue on motivation was reported, motivation was lower at 2km in the 20-km TT. However, despite it was not significant, motivation appeared to be higher in the later stages of the TT in the mental fatigue condition compared to the control condition. In terms of perceived exertion, multiple studies [16, 17, 31, 33] were not able to explain their observed reduction in performance through an increased perceived exertion. In contrast, and substantiating the previously observed increase in perceived exertion when mentally fatigued [36, 41, 42], Pires et al. [23], Slimani et al. [24] and Veness et al. [32] did observe higher RPE when physically performing in a mentally fatigued state. In the study of Pires et al. [23] absolute RPE throughout the TT was not higher when mentally fatigued, but relative to power output they were. Added up to the results of the studies included in our systematic review it can be concluded that motivation does not play a role in the mental fatigue-induced decrease in endurance performance, whilst RPE does certainly seem to be a mediator of this effect.

In terms of sport-specific psychomotor performance, the first three studies on mental fatigue [42, 45, 46], that were already cited in our published systematic review (see Chapter 2), all indicated the mental fatigue-induced performance impairment was not mediated by an altered motivation. In addition to motivation, Badin et al. [45] also assessed RPE and suggested mental fatigue might increase RPE related to a soccer-specific SSG. From the studies published after April 2016, only our own study (see Chapter 4) and Veness et al. [32] assessed motivation towards the upcoming physical task. In both it was found that motivation was unaffected by mental fatigue. In addition only in the studies of Le Mansec et al. [20] and Moreira et al. [28] perceived exertion was assessed. Le Mansec et al. [20] reported that RPE tended to be increased when mentally fatigued. Future studies looking into the possible role of other possible psychological determinants of psychomotor performance (e.g. self-efficacy, self-esteem, attentional focus [49]) could provide additional valuable insights on the possible psychological mechanisms behind the mental fatigue-induced psychomotor performance decrease.

6.3 Potential mechanisms

Based on the obtained results in the present PhD and section 6.2.2 it is clear mental fatigue impairs multiple aspects of physical performance. This apparent link between mental fatigue and physical performance opens up the discussion on the possible underlying mechanisms. In section 6.2.3 and 6.2.4 the physiological and psychological alterations associated with the mental fatigue-induced impairments in performance have been listed and discussed, question is however still how a preceding cognitive task can induce such alterations during a subsequent physical task.

Broadening our point of view and looking at the effects of mental fatigue on human performance (i.e. physical and cognitive performance in a wide variety of tasks) teaches us that multiple models have already been proposed to account for the mental fatigue-induced impairments in human performance [35]. Within these models, two major hypotheses, around which all models are structured, can be recognized: 1) a depletable physiological resource and 2) an effort-based decision. These two hypotheses represent the ever-returning dichotomy between a purely physiological model to explain a certain phenomenon – in the present case the link between mental fatigue and physical performance – and a purely psychological model. Despite their differences, both models have the similar assumption that the effects of mental fatigue on human performance occur due to similarity across two tasks that follow up on each other (e.g. similar executive function systems that are engaged). This similarity will eventually lead to decrements in performance on the second task. The difference is that the physiological model assumes that these carry-over effects from task 1 to task 2 are explained by a depleted physiological resource, while the psychological model postulates that cost-benefit computations underlie these carry-over effects. Both models are able to provide compelling evidence in their favour, however it will most probably be a combination of both models that succeeds in accounting for all observed findings concerning mental fatigue and human performance.

6.3.1 Endurance performance

Marcora et al. [36] made a first attempt to explain the link between mental fatigue and endurance performance by integrating both the physiological and the psychological point of view. This attempt was based on the results obtained in their first study on the topic [36], in which a 90-min cognitive task was followed by a physical endurance task. Performance on task 2 (i.e. the physical endurance task) was found to be impaired. This was associated with an increased perceived exertion. Both the employed 90-min cognitive task and the exertion perceived during physical tasks have already been associated with anterior cingulate cortex-activity and as such a similar brain region is employed in the cognitive task and the subsequent physical task. Psychologically, Marcora et al. [36] indicated that these carry-over effects were translated in an increased perceived exertion. Neurophysiologically these carry-over effects might be understood as changes in tonic neurotransmitter and/or neuromodulator levels in the executive function system that is employed in both the cognitive and the physical task (i.e. anterior cingulate cortex). This possible psychobiological explanation of the carry-over effects from mental fatigue to endurance performance can be substantiated by research that demonstrates that alterations in brain neurotransmitters affects perceived exertion and endurance performance.

The importance of brain neurotransmitters in endurance performance has already been underlined by Roelands et al. [50]. They showed that reboxetine (a noradrenaline re-uptake inhibitor) decreased whole-body endurance performance in normal and high ambient temperature. Interestingly, despite a decreased power output during the TT in this study there was no change in absolute RPE values, consequently increasing the perceived exertion to power output ratio (meaning less power output is generated for a same RPE value). The intake of methylphenidate [51] [a dopamine (DA) reuptake inhibitor] in contrast allowed subjects to maintain a higher power output and improve time trial performance in the heat, again without influencing absolute RPE values. This demonstrates that altered brain neurotransmission is able to affect whole-body endurance performance and that this effect is associated with an altered perceived exertion to power output ratio (in the case of DA, a decreased ratio). Klass et al. [52] showed that muscle endurance performance is affected in a similar way. A noradrenaline reuptake inhibitor reduced endurance time by 15.6%. This was associated with a greater rate of supraspinal impairment and an increase in perceived exertion. Participants experienced the same intensity of intermittent contractions as harder to perform after administration of a noradrenaline reuptake inhibitor, without affecting the fatigue-related intramuscular impairments [52].

Within the line of research on mental fatigue and endurance performance, Pageaux et al. [39, 41, 47] hypothesized that neural activity increases the extracellular concentration of adenosine (an inhibitory neurotransmitter; [53]) and that brain adenosine accumulation reduces endurance performance [54]. Subsequently they speculated that adenosine accumulation in the pre-supplementary motor area and anterior cingulate cortex (due to a mentally fatiguing task) could also explain in part the higher than normal perceived exertion during an endurance exercise in a mentally fatigued state. This hypothesis was recently supported and extended in a theoretical review of Martin and colleagues [55]. Unfortunately, there is no study that demonstrates that mentally fatigued individuals have increased adenosine in specific areas and that this is associated with the mental fatigue-induced endurance impairment. Nonetheless, the above points out that mental fatigue-induced neurotransmitter-alterations might partly mediate the negative effect of mental fatigue on endurance performance. And, rather than only focussing on adenosine, mental fatigue will probably affect neurotransmitter systems in multiple brain regions and the summation of these alterations might explain the increased perceived effort during an endurance performance in a mentally fatigued state.

6.3.2 Sport-specific psychomotor performance

In Chapter 4 it becomes clear mental fatigue not only impairs endurance performance, but also sport-specific psychomotor performance. More specifically mental fatigue impaired the response time to complex stimuli in both the badminton players and the controls. This is in accordance with previous studies on the effect of mental fatigue on cognitive performance [9-11], showing that executive control is compromised by mental fatigue, but more automatic cognitive processing is relatively insensitive to this state. Moreover it is also in accordance with other research on the effect of mental fatigue and sport-specific psychomotor performance (see section 6.2.2).

In an attempt to explain the link between mental fatigue and sport-specific psychomotor performance, according to the proposed models on mental fatigue and human performance, similarities across the cognitive and the physical task must be distinguished. In both the 90-min Stroop task and the 7-min visuomotor response task response inhibition was an important executive function determining task performance. In the Stroop task response inhibition was necessary for 100% of stimuli, while in the visuomotor task this function was employed for 25% of the stimuli. Both tasks also worked with a general response rule and an exceptional response rule, meaning that participants had to switch rules depending on specific colour features of the stimuli. This task switching ability was necessary in 25% of the stimuli, as 25% of the stimuli presented in the Stroop task and in the visuomotor task contained the specific feature (i.e. in the Stroop when the letters of the word were coloured in red; in the visuomotor task when the pad lighted op in the colour blue) that indicated that participants had to switch to the exceptional rule in order to respond correctly. These two executive functions, response inhibition and task switching ability, represent two important similarities across the cognitive and the physical task that might explain why carry-over effects from the cognitive task to the physical task were observed in Chapter 4. A similar mechanism might underlie the carry-over effects observed in the psychomotor performance-studies included in section 6.2.2 . The SSG employed in the basketball-study of Moreira et al. [28] and in the soccer-study of Coutinho et al. [19] continuously drew upon response inhibition (e.g. giving a pass or not) and task-switching ability (e.g. defending vs attacking), while in the study of Le Mansec et al. [20] response inhibition and anticipation can be recognized as similarities between the 90-min AX-CPT and the table tennis performance test.

Neurophysiologically these carry-over effects might again be understood as changes in tonic neurotransmitter and/or neuromodulator levels in the executive function system that is employed in both the cognitive and the physical task. Performance on such short, fixed duration visuomotor tasks is less determined by perceived exertion and as such the subjective signature of the mental fatigue-effects on physical performance (i.e. increased perceived exertion) is less visible. This however does not mean the neurophysiological alterations associated with mental fatigue are not present. The present visuomotor task can be termed a perceptual switching task (i.e. attention must be actively switched between perceptual features (e.g. colour) in order to select the appropriate, task-relevant response), the same holds true for the Stroop task [56]. Specifically for this type of switching the dorsal premotor cortex is preferentially recruited [56]. A brain region that, in addition to motor planning and motor execution, is involved in learning and applying rule-based associations between perceptual features of stimuli and responses [57]. As such this region, and neurophysiological alterations within this region, is a key candidate to play a role in the mental fatigue-induced impairment in task-switching ability during a psychomotor task.

6.4 Countermeasures

All the above points out that mental fatigue has to be avoided, certainly in situations where optimum performance is required, e.g. work setting, military operation, Olympic games, … . Therefore, an interest arose in possible countermeasures of mental fatigue. Multiple types of interventions have been put forward: pre-game/competition guidelines to avoid mental fatigue, strategies to counteract mental fatigue during games/competitions and training resistance to mental fatigue.

The most important pre-game/competition guideline that currently has been suggested to avoid the occurrence of mental fatigue is that mentally demanding tasks should be avoided before games/competitions. Tasks that regularly preceed a game/competition and could possibly trigger mental fatigue are for example interviews, emotion control and tactical meetings. Despite the general plausibility of counteracting mental fatigue by avoiding/limiting pre-game cognitive load (e.g. interviews, tactical meetings), this guideline has yet to be substantiated by experimental research. Surveys/interviews to chart the mental demands of high-level sport participation will allow researchers to understand which tasks, if any, players find mentally fatiguing [58], and if avoidance/restriction of these tasks would result in a reduction of mental fatigue. In terms of strategies to counteract the negative effects of mental fatigue during games/competitions, both psychological and nutritional interventions have been proposed. Psychologically, a cognitive load-reducing strategy appears to be promising. Brick et al. [59] demonstrated that external control over pacing (e.g. drafting in a race) may facilitate performance, possibly mediated through reducing the cognitive load and promoting appropriate attentional strategies that optimize performance. In light of the psychobiological model [48], increasing motivation also seems to be a valid way to counteract mental fatigue and its negative effects. Although motivational changes were concluded not to play a role in the mental fatigue-induced impairments in physical performance in multiple chapters included in this PhD, this does not rule out that increasing motivation could successfully counteract mental fatigue and its negative effects. In terms of cognitive performance, Hopstaken et al. [60] demonstrated that increasing motivation, by providing a monetary incentive near the end of a prolonged cognitively demanding task, reversed cognitive performance declines despite previous signs of mental fatigue. A study by Brown et al. [15] further substantiated this ability of motivation to counteract mental fatigue in a physical performance-setting. Increased motivation by a monetary incentive reversed the mental fatigue-induced decrease in performance in an endurance handgrip task. Caution is however warranted as Gergelyfi et al. [61] also altered the motivational state through monetary incentives during a 120-min Sudoku task and failed to compensate the effects of mental fatigue. Moreover, in two studies included in this PhD [43, 62] monetary incentives were provided to promote task engagement, and in both studies mental fatigue was still induced after a prolonged cognitive task. Motivation thus seems to possess the ability to counteract mental fatigue, yet only to a limited extend. Nutritionally, caffeine has been put forward as a promising intervention to counteract mental fatigue and its effects on physical performance [41]. The mental fatigue-counteracting properties of caffeine are attributed to its ability to easily cross the blood-brain barrier and bind to cell membrane receptors for adenosine, thus blocking the inhibitory effects of adenosine on neuro-excitability, neurotransmitter release and arousal [55]. Azevedo et al. [31] showed this experimentally, caffeine ingestion successfully reversed the mental fatigue-induced impairment in cycling time to exhaustion at 80% of the maximal power output. This positive effect of caffeine ingestion was accompanied by a tendency to an improvement in mood state (i.e. vigour). In addition, McLellan et al. [63] concluded that caffeine is an effective strategy to maintain physical performance during an overnight period of sleep loss at levels comparable to the rested state. A last option to counteract mental fatigue and the subsequent impaired physical performance is by training resistance to mental fatigue. A first insight on this matter was given by a study of Martin et al. [12], who designed a study to specifically assess whether level of training in endurance sport had any influence on the resistance to mental fatigue. Interestingly, they found that professional cyclists exhibited superior performance during a 30-min Stroop task compared to recreational cyclists, which is indicative of stronger inhibitory control. Moreover, professional cyclists displayed a greater resistance to the negative effects of mental fatigue on a 20-min cycling time trial than recreational cyclists [12]. In our own attempt to replicate these findings with badminton-athletes we could however not confirm these results (see Chapter 4). Multiple reasons could account for failing to confirm the results of Martin et al. [12], the two most prominent are: (1) more severe mental fatigue was induced in our study and (2) badminton-athletes were not of the same elite-level as the cyclists in the study of Martin et al. [12]. To explain the superior resistance to mental fatigue of elite athletes, Martin et al. [12] pointed to genetic and environmental factors (i.e. aerobic training required by professional road cycling may induce morphological and functional adaptations in the anterior cingulate cortex that increase resistance to mental fatigue). Further research is however necessary to determine what might explain the possible superior resistance to mental fatigue present in elite athletes.

In Chapter 5 of the present PhD a new possible countermeasure of mental fatigue was evaluated (i.e. serial mouth rinsing of a solution containing caffeine and maltodextrin) and found to be effective. Serially rinsing a caffeine and maltodextrin solution offers a suitable 'nutritional' countermeasure for those that want to restrict caloric intake or participate in the Ramadan. Perhaps more importantly, this specific study also resulted in further insights in the mediating mechanisms of mental fatigue. Multiple possible mechanisms for the effectiveness of serial CAF-MALT mouth rinsing are proposed in our mouth rinse-study. The mechanism that seems the most important is the brain activating properties of mouth rinsing. Mouth rinsing is known to activate multiple brain areas [64], e.g. the activation of specific brain regions (i.e. the anterior cingulate cortex and the right caudate that forms part of the striatum) known to produce DA [64, 65], and has also been shown to do so in the study performed in Chapter 5. Mental fatigue on the other hand has already been associated with alterations in the anterior cingulate cortex [36, 66-68]. This way, a mouth rinse containing caffeine and maltodextrin might be able to (partly) restore dopaminergic transmission in the striatum and anterior cingulate cortex and postpone mental fatigue by activating sensory neurons in the mouth and initiating a signal transduction cascade towards the brain. The sensory neurons that triggered this transduction cascade could be the neurons that caused the participants to score the CAF-MALT mouth rinse less pleasant (i.e. more bitter) than the placebo mouth rinse (see Chapter 5). At the end of each trial participants had to rate the pleasantness of the sweet/bitterness taste of the mouth rinse, and participants scored the CAF-MALT mouth rinse as significantly less pleasant/more bitter (-0,9 on a 5-point scale) than the placebo mouth rinse. This clearly indicates a taste-difference was present between both mouth rinses and could explain why a specific transduction cascade was triggered in the CAF-MALT mouth rinse-trial and not in the placebo mouth rinse trial. Kishi et al. [69] reported that tasting bitter is associated with activation of the anterior cingulate cortex and as such substantiate that the CAF-MALT mouth rinse might have triggered a specific transduction cascade.

6.5 Strengths and weaknesses

The main research findings in this thesis provide valuable insights on the link between mental fatigue and physical performance and opens doors towards further research on the mechanisms underlying this link. Meaningful advances in the field of mental fatigue and physical performance were made in the present PhD due to the focus on 1) diverse aspects of physical performance (i.e. endurance and psychomotor skills), 2) diverse environmental conditions (i.e. normal and heat), 3) possible applicable countermeasures of mental fatigue and 4) diverse levels of training-status (i.e. novice, recreational and competitive). However, like everything, also this thesis has its strengths and weaknesses. A first point of criticism could be that the sample sizes used in the studies embedded in this thesis are fairly small. A small sample size has two important implications, 1) a reduced chance of detecting a true effect, and 2) a reduced likelihood that a statistically significant result reflects a true effect [70]. Although sample sizes were fairly small, these were based on a priori sample size calculations in which a power of at least 80% was always set. Moreover, all conducted studies included in the present PhD were designed as crossover studies, meaning that each participant in every study was included in every condition and thus functioned as its own control, thereby reducing variability. These precautionary measures make us confident that the observed effects in the present PhD are true effects. In addition, the multiple recently published studies confirming our observed effects seem to justify this confidence, as false effects are generally difficult to reproduce. Despite the confidence in the observed effects being true effects, we acknowledge that caution is warranted in the interpretation of three- and four-way ANOVA's that were used in multiple chapters.

Electroencephalography (EEG) is a brain measuring technique that was used in multiple studies in the present PhD. This technique can be considered a real strength as it provided an objective window on the brain's functioning and enabled us to objectify the psychobiological changes associated with mental fatigue. A disadvantage of this technique is however its poor spatial resolution, which makes it less useful than magnetic resonance imaging to pinpoint the exact source of the recorded brain activity. Moreover, EEG-electrodes are applied to the scalp and are thus particularly equipped to measure brain activity originating from the cortex, while measuring subcortical brain activity with EEG is more challenging. That said, there are up to date advanced techniques to adequately analyse electroencephalographical signals and counteract these known downsides. In the present PhD brain activity was recorded with thirty-two active Ag/AgCl electrodes, enabling us to reduce artefacts in the recorded brain activity by applying an independent component analysis, which resulted in the removal of recurrent artefacts throughout each electrode-recording. Future research might make use of other specific analytical techniques such as standardized low-resolution brain electromagnetic tomography [71] to analyse and quantify mental fatigue in further detail. To further increase our knowledge on the link between mental fatigue and physical performance, electroencephalography might prove to be extremely valuable in future studies. Although it has its downsides, it offers excellent temporal resolution and with advances in wireless hardware and equipment portability, allows a freedom of movement almost impossible to achieve with other neuroimaging technologies [72].

A last important point to discuss in this section is the transferability of the observed results in the present PhD. Specifically in order to translate the results of research on mental fatigue and physical performance to the fatigue often associated with aging and/or disease. It is important to make the distinction between an acute form of mental fatigue induced by mental exertion and the more chronic mental fatigue and cognitive impairment associated with aging or disease (e.g. cancer, chronic fatigue syndrome and depression). Despite some similarities between both phenomena (e.g. impaired cognitive performance, increased feeling of fatigue), chronic fatigue is not necessarily related to mental exertion (e.g. aging, disease) and therefore is not completely the same as acute mental fatigue induced by prolonged cognitive activity. Nevertheless, hypotheses have been suggested that repeated acute mental fatigue may lead to chronic fatigue [73] and as such it seems important to promote communication between research on mental fatigue and physical performance and research on mental fatigue and other aspects of daily life.

6.6 Future research avenues

Undoubtedly the line of research on mental fatigue and physical performance will give rise to the development of a number of relevant research avenues. Based on the results obtained in the present PhD important research questions that should be addressed in the future are:

Which are the (neuro)physiological mechanisms of the mental fatigue-induced physical performance impairment?

Despite the expanding knowledge on the behavioural effects of mental fatigue in sports science, the neurophysiological mechanisms of the impairment in physical performance have yet to be elucidated. To provide applicable countermeasures for the mental fatigue-induced decrease in physical performance, it is of great importance to keep on progressing in the search for the (neuro)physiological mechanisms of this phenomenon. Not only from a scientific point of view this is of importance, also from an athlete's/coach's point of view it is. At the very top level perceptual-cognitive skills might provide the edge in a competitive field where physical qualities are somewhat levelled between different athletes [74]. Progress in this search for neurophysiological mechanisms can be attained in different ways, use of advanced measuring equipment is one way. Substantial progress has been made in developing state-of-the-art neuroscience methods (i.e. functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS) and EEG) that can be used during local exercise and even outside a laboratory environment [75]. EEG is one of the two main non-invasive functional neuroimaging methods (besides NIRS) suitable for use during exercise. The equipment becomes portable, it has a relatively low cost, is easy to handle and data acquisition is fast. EEG has already been shown to provide valuable information on mental fatigue in the field of cognitive neuroscience [60, 62, 66], applied during physical performance it might do the same in sports science.

Another way to increase our understanding of the mental fatigue-induced impairment in physical performance is the use of specific designs to assess whether the resistance to mental fatigue is trainable. A few steps have already been taken in this direction ([12] and Chapter 4), with conflicting evidence as a result. Martin et al. [12] reported that professional cyclists have superior resistance to mental fatigue compared to recreational cyclists, while we ourselves observed that psychomotor skills were similarly impaired in athletes and controls. The importance of this research question (i.e. are top-level athletes more resistant to mental fatigue than others) and the presented conflicting evidence calls for further attention in future studies.

Ecological validity of mentally fatiguing tasks?

The demands of real life physical events/competitions are physically but also cognitively high, as is shown by the metacognitive framework of Brick et al. [76]. Therefore, such real life physical events/competitions are probably not only physically fatiguing, but also mentally fatiguing. Up to date, the role of mental fatigue in physical performance has been evaluated by isolating the executive function processes that are employed during physically performing (e.g. response inhibition, task switching, …) and thought to be mentally fatiguing. The most straightforward way to do so is by selecting a task that stresses specifically these executive function processes (i.e. a cognitive task: e.g. Stroop task) and evaluate its effect on physical performance. However, like many others in the field [27, 46], we have already pointed out the necessity for future research to be conducted in a more applied way. One way could be by making the cognitive task more sport-specific. The outcome measure used in the study of Smith et al. [46] to evaluate soccer-specific decision-making skill could for example also be used as a sport-specific mentally fatiguing task. Another way to increase applicability of the results in this line of research was demonstrated by Coutinho et al. [27]. They [27] attempted to induce mental fatigue in an ecologically valid way, by employing a 20-min whole-body coordination task, requiring motor coordination, sustained attention, cognitive processing and perceptual skills. To increase the tasks' attentional and cognitive demands, players were also required to perform the coordination movements while juggling a tennis ball. On top of that, as soon as the participant's performance increased, a new exercise was introduced. For the control condition, players were required to perform light general aerobic exercises such as skipping, jogging, running backwards, and side stepping (i.e. exercises with low cognitive demand and a similar physical pattern as the mental fatigue task) [27]. This method resulted in a greater increase in subjective mental fatigue (measured with a VAS) after the mental fatigue task (PRE: ~10 → POST: ~55) compared to the control task (POST: ~10 → POST: ~15) and was thus demonstrated to be successful. Nonetheless, methodological considerations such as the differences in physical (heart rate) response between conditions, sport specificity and response bias must be considered [58]. Specifically for football, Thompson et al. [58] suggested a few valid recommendations for future research: develop tasks with a high level of contextual interference, replicate match-play scenarios in terms of audio and/or visual distractions and develop tasks with an intermittent character. Besides progressing to a more applied way of evaluating the role of acute mental fatigue in physical performance, evaluating the chronic effects of mental exertion is also an important progression in this field of research. The chronic psychological load that elite athletes are exposed to and its possible role in risk of illness and injury have been considered and emphasized by two International Olympic Committee consensus statements [77, 78]. This psychological load encompasses negative life-event stress, daily hassle and sports-related stress (e.g. feeling of insufficient breaks and rest, stiff and tense muscles, and feeling vulnerable to injuries), but also personality variables such as trait anxiety, state anxiety, stress susceptibility, type A behaviours, trait irritability and mistrust, as well as maladaptive coping strategies [77]. In the consensus statement on load and risk of injury, fatigue is one of the proposed mechanisms by which psychological stress responses is thought to increase injury risk [77]. The importance of chronically monitoring psychological load is demonstrated by Ivarsson et al. [79] who evidenced that trait anxiety, negative-life-event stress and daily hassle are significant predictors of injury. This highlights the need for athletes, coaches and medical practitioners to attempt to monitor and reduce mental fatigue. Future studies should aim to adopt this more ecological way of studying mental fatigue, as it will greatly improve the transferability of the observed results in mental fatigue-research. In addition it will also provide important insights in the mentally fatiguing properties of physical activity on its own.

6.7 Conclusion

The main research findings from this PhD were:

- Mental fatigue impairs endurance performance and the underlying mechanism of this impairment appears to be a higher than normal perceived exertion.
- Mild mental fatigue does not affect endurance performance in the heat.
- Subjective thermal strain impairs endurance performance in a temperate environment.
- Mental fatigue decreases open skill-visuomotor performance in controls as well as badminton players.
- Serial caffeine-maltodextrin mouth rinsing counteracts subjective, behavioural, and electrophysiological measures of mental fatigue.

Overall these results point out mental fatigue has important implications in physical performance, and that these are mediated by a strong neurophysiological and psychobiological component. The present PhD forms an excellent basis for future studies exploring the impact of mental fatigue on physical performance. Continuation of this research is of extreme importance as mental fatigue - and other neurophysiological and psychobiological mediators of physical performance - have only recently gained attention in sports science. Besides being an important topic in sports science, mental fatigue is an issue that is encountered in a multitude of settings that are encountered in daily life (work, driving a car, disease, …) and as such this research also forms an excellent basis for translational research.

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Summary

The ubiquitous presence of fatigue in our everyday life has caused the topic of fatigue to sprout in many specific research fields such as exercise physiology, cognitive psychology, medicine and engineering. Fatigue is associated with the urge to sleep at the end of a busy day, the need for coffee in the morning, the burning sensation in our legs and lungs at the end of an intensive physical workout, the feeling of a much-needed break in the afternoon during a work-day, the problems with staying attentive during a prolonged drive, … . Fatigue can cause substantial limitations in mental, physical and/or social functioning, resulting in considerable social and economic impacts (e.g. loss of contact with friends, increased medical costs, absenteeism from work).

Fatigue has a vast amount of definitions, with a different focus in each area of expertise. This omnipresence of fatigue has its advantages and disadvantages, one of the main disadvantages is probably that different research lines of fatigue co-exist without any interaction. Subsequently the possible breakthroughs this interaction could trigger are missed. Within sports science the urge to explain why and how people fatigue has intrigued scientist for decades, and also within this area different lines of research on fatigue (e.g. exercise physiology and psychology) could benefit from increased interaction with one another. Recent advances have been made however to converge both. A research topic that has played an important role in this convergence is mental fatigue. Mental fatigue is a research topic that contains aspects of both exercise physiology and psychology and as such might prove to be a valuable asset in the search for mechanisms of fatigue in sports science. This line of mental fatigue attempts to provide some further insights in the mechanisms behind the underperformance on physical tasks following the execution of a prolonged demanding cognitive task. In attempting to do so, the role of physiological and psychological factors in physical performance is assessed.

The research topic mental fatigue has only recently gained attention and as such the present PhD dissertation aimed to further explore the link between mental fatigue and physical performance. In order to do so, it consists of one systematic review of the literature and four randomized controlled trials. All five manuscripts were written as stand-alone papers of which four have been accepted and one is submitted in relevant international exercise physiology, psychology and behavioural neuroscience journals.

In order to provide a clear overview on the current body of knowledge on the effect of mental fatigue and physical performance, a first aim in this PhD was to conduct a systematic review of the available literature on the topic (see Chapter 2). This review pointed out that mental fatigue impairs endurance performance, and the underlying mechanism of this impairment appears to be a higher than normal perceived exertion. Physiological variables traditionally associated with endurance performance (heart rate, blood lactate concentration, oxygen uptake, cardiac output) were not directly affected by mental fatigue during and after endurance performance. Maximal strength, power, and anaerobic work were not affected by mental fatigue. This led to the conclusion that duration, intensity and a cognitive component in the physical task appear to be important moderating factors in the effect of mental fatigue on physical performance. In our search to further explore the link between mental fatigue and physical performance we aimed: (1) to assess in further detail the possible moderating role of heat in the effect of mental fatigue on endurance performance (see Chapter 3), (2) to observe the impact of mental fatigue on sport-specific psychomotor skills (see Chapter 4) and (3) to evaluate a possible countermeasure of mental fatigue (see Chapter 5). These aims resulted in the following research questions:

- **<u>Research Question 1:</u>** Does mental fatigue affect physical performance, and if yes, what are the underlying factors? (Chapter 2)

- **Research Question 2:** Does mental fatigue affect endurance performance in the heat? (Chapter 3)
- **Research Question 3:** Does a heat pad, locally applied to the upper back, impair endurance performance? (Chapter 3)
- **Research Question 4:** Does mental fatigue impair sport-specific psychomotor performance? (Chapter 4)
- **Research Question 5:** Does level of training affect the impact of mental fatigue on sport-specific psychomotor performance? (Chapter 4)
- **Research Question 6:** Does serial caffeine-maltodextrin mouth rinsing counteract mental fatigue? (Chapter 5)

In Chapter 3 a 45-min Stroop task induced a 'mild form' of mental fatigue in the heat (30°C). This mild mental fatigue did not influence participants' psychological or physiological responses during the endurance task or their endurance performance in the heat. These findings could indicate that heat is a moderating factor of the mental fatigue-induced endurance impairment. It is plausible that a similar psychobiological mechanism may explain the effects of heat stress and mental fatigue on perception of effort and why the effects of the two stressors do not summate. In other words, in conditions of thermal discomfort, mild mental fatigue may not lead to a further increase in negative valence and perception of effort. In the follow-up study in Chapter 3, subjective thermal strain was demonstrated to be a mediator of the heat-induced performance impairment, independently from the physiological strain that is associated with it. This substantiates that at least a part of the heat-induced performance impairment is mediated by a psychobiological mechanism and enlarges the probability that heat stress and mental fatigue may share a common psychobiological mechanism, i.e. the negative valence of emotions associated with both heat stress and mental fatigue increases perception of effort and subsequently impairs physical performance. From a more applied point of view these results justify the use of specific techniques aiming to reduce subjective thermal strain (e.g. menthol spray).

From the results observed in Chapter 4 it could be concluded that mental fatigue decreased open skill-visuomotor performance in controls as well as badminton players. These results substantiate that mental fatigue does not only impair endurance sports, but also impairs sport-specific psychomotor performance (e.g. open skill-visuomotor performance). Specifically executive control (i.e. the control to overrule an automatic response) was compromised by mental fatigue during the sport-specific psychomotor task, more automatic cognitive processing was relatively insensitive to this state. In addition, these results also demonstrate that high level athletes are not immune to mental fatigue.

In Chapter 5 the mental fatigue-counteracting properties of serially rinsing the mouth with a caffeine-maltodextrin solution were evaluated. It was demonstrated that a serial caffeine-maltodextrin mouth rinse counteracts subjective, behavioural, and electrophysiological mental fatigue. Practically this intervention provides the opportunity to avoid the, sometimes, unwanted side effects of caffeine and/or maltodextrin intake. Caffeine intake, for example, can cause tremors, nausea, nervousness, increased levels of anxiety, or gastrointestinal distress. In addition, it may also adversely affect sleep patterns. Ingesting carbohydrates might also be forbidden (e.g. during Ramadan) or unwanted for health reasons (e.g. diabetes and obesity), especially in the form of energy drinks. Mechanistically these counteracting properties might be explained via the mouth rinse activating sensory neurons

in the oral cavity, initiating a signal transduction cascade towards the brain and subsequently restoring dopaminergic brain transmission.

Overall these results point out that mental fatigue has important implications in physical performance, and that these are mediated by a strong neurophysiological and psychobiological component. The present PhD forms an excellent basis for future studies exploring the impact of mental fatigue on physical performance. Continuation of this research is of extreme importance as mental fatigue - and other neurophysiological and psychobiological mediators of physical performance - have only recently gained attention in sports science. Besides being an important topic in sports science, mental fatigue is an issue that is encountered in a multitude of settings that are encountered in daily life (work, driving a car, disease, …) and as such this research also forms an excellent basis for translational research.

Samenvatting

De alomtegenwoordige aanwezigheid van vermoeidheid in ons dagelijks leven heeft ertoe geleid dat het onderzocht wordt in veel specifieke onderzoeksgebieden zoals: inspanningsfysiologie, cognitieve psychologie, geneeskunde en technologie. Vermoeidheid wordt geassocieerd met de drang om te slapen aan het einde van een drukke dag, de behoefte aan koffie in de ochtend, het brandende gevoel in onze benen en longen aan het einde van een intensieve fysieke training, het gevoel van een broodnodige pauze tijdens een werkdag, de problemen om aandachtig te blijven tijdens een langere rit met de auto, … . Vermoeidheid kan aanzienlijke beperkingen in het mentale, fysieke en/of sociale functioneren veroorzaken, welke kunnen resulteren in aanzienlijke sociale en economische gevolgen (vb. verliezen van contact met vrienden, ziekteverzuim op het werk, kosten medische/psychologische begeleiding, …).

Vermoeidheid kent vele definities, met een andere focus in elk expertisegebied. Dit heeft zijn voor- en nadelen, een van de belangrijkste nadelen is waarschijnlijk dat verschillende onderzoekslijnen van vermoeidheid naast elkaar bestaan, zonder enige interactie. Het gevolg is dat de mogelijke doorbraken die deze interactie zou kunnen veroorzaken gemist worden. Ook binnen de sportwetenschap bestaat de drang om uit te leggen waarom en hoe mensen moe worden, en ook binnen dit gebied bestaan verschillende lijnen van onderzoek naar vermoeidheid (bijvoorbeeld inspanningsfysiologie en psychologie) die zouden kunnen profiteren van een toegenomen interactie met elkaar. Recente vooruitgang is echter geboekt om deze beide onderzoekslijnen samen te brengen, een onderzoeksthema dat een rol heeft gespeeld en dat hoogstwaarschijnlijk nog een belangrijke rol zal spelen in deze convergentie is mentale vermoeidheid. Mentale vermoeidheid is een onderzoeksonderwerp dat aspecten van zowel inspanningsfysiologie als psychologie bevat en als zodanig een waardevolle aanwinst blijkt bij het zoeken naar mechanismen van vermoeidheid in de sportwetenschap. Deze onderzoekslijn naar mentale vermoeidheid probeert inzichten te verschaffen in de mechanismen achter de mindere fysieke prestatie na de uitvoering van een langdurig veeleisende cognitieve taak. In een poging om dit te doen, wordt de rol van fysiologische en psychologische factoren in fysieke prestaties beoordeeld.

Het onderzoeksthema mentale vermoeidheid is pas onlangs op de voorgrond getreden en als zodanig was het doel om in dit proefschrift het verband tussen mentale vermoeidheid en fysieke prestaties verder te onderzoeken. Om dit te doen is dit proefschrift opgebouwd uit een systematische review van de literatuur en vier gerandomiseerde gecontroleerde studies. Alle vijf manuscripten werden geschreven als op zichzelf staande papers waarvan er vier zijn geaccepteerd en één is ingediend in relevante internationale fysiologische, psychologische, neurowetenschappelijke wetenschapstijdschriften.

Om een duidelijk overzicht te geven van de huidige kennis over het effect van mentale vermoeidheid op fysieke prestaties, was een eerste doel van dit doctoraat om een systematische review van de beschikbare literatuur over dit onderwerp uit te voeren (zie hoofdstuk 2). Deze review maakte duidelijk dat mentale vermoeidheid de uithoudingsprestatie doet dalen, en het onderliggende mechanisme van deze daling lijkt een hoger dan normaal gevoel van inspanning te zijn. Fysiologische variabelen die traditioneel geassocieerd worden met uithoudingsvermogen (hartslag, bloed lactaat, zuurstofopname, cardiale output) werden niet direct beïnvloed door mentale vermoeidheid tijdens en na de uithoudingsprestatie. Maximale kracht, kracht en anaerobe arbeid werden niet beïnvloed door mentale vermoeidheid. Dit leidde tot de conclusie dat duur, intensiteit en een cognitieve component van de fysieke taak belangrijke modererende factoren lijken te zijn in het effect van mentale vermoeidheid op de fysieke prestaties. In onze zoektocht om het verband tussen mentale vermoeidheid en fysieke prestaties verder te ontrafelen hebben we geprobeerd: (1) om de mogelijke modererende rol van warmte in het effect van mentale vermoeidheid op de uithoudingsprestaties te achterhalen (zie hoofdstuk 3), (2) de impact van mentale vermoeidheid op sport-specifieke psychomotorische vaardigheden nader te beoordelen (zie hoofdstuk 4) en (3) om een mogelijke tegenmaatregel voor de negatieve effecten van mentale vermoeidheid te evalueren (zie hoofdstuk 5). Deze doelen resulteerden in de volgende onderzoeksvragen:

- **Onderzoeksvraag 1:** Beïnvloedt mentale vermoeidheid fysieke prestaties en, zo ja, wat zijn de onderliggende factoren die dit veroorzaken? (Hoofdstuk 2)
- **Onderzoeksvraag 2:** Beïnvloedt mentale vermoeidheid het uithoudingsvermogen in de hitte? (Hoofdstuk 3)
- **Onderzoeksvraag 3:** Beïnvloedt een warmte-kussen, lokaal aangebracht op de bovenrug, het uithoudingsvermogen? (Hoofdstuk 3)
- **Onderzoeksvraag 4:** Vermindert mentale vermoeidheid de sport-specifieke psychomotorische prestatie? (Hoofdstuk 4)
- **Onderzoeksvraag 5:** Heeft het trainingsniveau invloed op de impact van mentale vermoeidheid op sport-specifieke psychomotorische prestatie? (Hoofdstuk 4)
- **Onderzoeksvraag 6:** Countert herhaalt de mond spoelen met een cafeïne-maltodextrine solutie mentale vermoeidheid? (Hoofdstuk 5)

In Hoofdstuk 3 werd door een Stroop-taak van 45 minuten een 'milde vorm' van mentale vermoeidheid met succes opgewekt in de hitte (30°C). Deze had echter geen invloed op de psychologische of fysiologische variabelen tijdens de uithoudingstaak, noch op de uithoudingsprestatie zelf. Deze bevinding bevestigt dat hitte een mogelijke moderator zou kunnen zijn van het effect van mentale vermoeidheid op het uithoudingsvermogen. Het is aannemelijk dat een vergelijkbaar psychobiologisch mechanisme de effecten van hitte en mentale vermoeidheid op de perceptie van inspanning kan verklaren. Indien dit klopt, kan dit ook verklaren waarom de effecten van de twee stressoren niet optellen. Met andere woorden, bij condities van thermisch ongemak kan het zijn dat het effect van lichte mentale vermoeidheid op de perceptie van inspanning vervaagt. In de vervolgstudie in hoofdstuk 3 werd aangetoond dat subjectieve thermische stress een moderator is van de hitte-geassocieerde beperking in uithoudingsprestatie, en dit onafhankelijk van de fysiologische variabelen die meestal geassocieerd worden met het verminderen van prestatie in de hitte. Dit bevestigt dat ten minste een deel van de hitte-geassocieerde prestatiebeperking wordt gemedieerd door een psychobiologisch mechanisme en vergroot de waarschijnlijkheid dat hitte en mentale vermoeidheid een gemeenschappelijk psychobiologisch mechanisme hebben. Met andere woorden, de negatieve valentie van emoties geassocieerd met zowel hitte als mentale vermoeidheid verhoogt de perceptie van inspanning en verslechtert vervolgens de fysieke prestatie. Vanuit een meer toegepast gezichtspunt rechtvaardigen deze resultaten het gebruik van specifieke technieken die gericht zijn op het verminderen van subjectieve thermische stress (bijvoorbeeld mentholspray).

Uit de resultaten die in hoofdstuk 4 zijn waargenomen, kan worden geconcludeerd dat mentale vermoeidheid visuomotorische prestaties verminderd bij zowel niet-atleten als badmintonspelers. Deze resultaten bevestigen dat mentale vermoeidheid niet alleen de duursporten schaadt, maar ook sport-specifieke psychomotorische prestaties. In dit hoofdstuk kwam naar voor dat specifiek de executieve controle (d.w.z. iemands controle om een automatische reactie te negeren) werd aangetast door mentale vermoeidheid tijdens de sport-specifieke psychomotorische taak. Meer automatische cognitieve verwerking was echter relatief ongevoelig voor deze toestand. Bovendien laten deze resultaten ook zien dat topsporters niet immuun zijn voor mentale vermoeidheid.

In Hoofdstuk 5 werd nagegaan of het herhaaldelijk spoelen van de mond met een cafeïne-maltodextrine-oplossing een tegenmaatregel kan zijn voor de negatieve effecten van mentale vermoeidheid. Er werd aangetoond dat een seriële cafeïne-maltodextrine mondspoeling subjectieve, gedragsmatige en elektrofysiologische effecten van mentale vermoeidheid tegengaat. Praktisch gezien biedt deze interventie de mogelijkheid om de, soms ongewenste, bijwerkingen van cafeïne en/of maltodextrine-inname te voorkomen. Cafeïne-inname kan bijvoorbeeld misselijkheid, nervositeit, verhoogde angstniveaus of gastro-intestinale klachten veroorzaken. Bovendien kan het ook het slaappatroon negatief beïnvloeden. Het innemen van koolhydraten kan ook verboden (bijvoorbeeld tijdens Ramadan) of ongewenst zijn om gezondheidsredenen (bijvoorbeeld diabetes en obesitas), in het bijzonder in de vorm van energiedranken. Mechanistisch gezien kunnen deze tegenwerkende eigenschappen worden verklaard via de mondspoeling die sensorische neuronen in de mond activeert, waardoor een signaaltransductiecascade naar de hersenen wordt geïnitieerd en vervolgens dopaminerge hersentransmissie wordt hersteld.

De resultaten van dit proefschrift wijzen erop dat mentale vermoeidheid belangrijke implicaties heeft voor de fysieke prestaties en dat deze worden gemedieerd door een sterke neurofysiologische en psychobiologische component. Het huidige doctoraat vormt een uitstekende basis voor toekomstige onderzoeken naar de impact van mentale vermoeidheid op de fysieke prestaties. Voortzetting van dit onderzoek is van extreem belang omdat mentale vermoeidheid - en andere neurofysiologische en psychobiologische bemiddelaars van fysieke prestaties - pas onlangs aandacht hebben gekregen in de sportwetenschap. Behalve dat het een belangrijk onderwerp is in de sportwetenschap, is mentale vermoeidheid een probleem dat wordt aangetroffen in een veelheid aan situaties die we dagelijks tegenkomen (werk, autorijden, ziekte, ...). Net daarom vormt dit onderzoek ook een uitstekende basis om de resultaten te proberen vertalen naar andere onderzoeksgebieden.

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List of publications – scientific CV

Curriculum Vitae

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- Verschueren J, Tassignon B, Pluym B, Van Cutsem J, Verhagen E, and Meeusen R. Bringing context to balance: development of a reactive balance test within the injury prevention and return to sport domain. 2019. Archives of Physiotherapy. https://doi.org/10.1186/s40945-019-0057-4

International and national presentations / Invited speaker

- Oral presentation on 'The training and competing in the heat conference in Doha, Qatar, 23-24 March 2014'.
  Title presentation: *the influence of heat stress and hypoxia on exercise performance*
  Jeroen Van Cutsem, Dirk Vissenaeken, Gino Dhondt, Nathalie Pattyn, Romain Meeusen, Bart Roelands
- Oral presentation on 'Transities', 19th VK Symposium (Vereniging voor Kinesiologie), Antwerp, 12 December 2014.
  Title presentation: *The influence of a mild thermal challenge and severe hypoxia on exercise performance and serum BDNF.*
  Jeroen Van Cutsem, Nathalie Pattyn, Dirk Vissenaeken, Gino Dhondt, Kevin De Pauw, Cajsa Tonoli, Romain Meeusen, Bart Roelands.
- Mini-oral presentation on 'ECSS' in Malmö, Sweden, 24-27 June 2015.
  Title presentation: *The effect of mental fatigue on physical performance, a systematic review.*
  Jeroen Van Cutsem, Samuele Marcora, Romain Meeusen, Bart Roelands.
- Oral presentation on '1st Endurance Research Conference' in Kent, UK, 2-4 September 2015
  Title presentation: *Impact of mental fatigue on a preloaded time trial in the heat*.
  Jeroen Van Cutsem, Kevin De Pauw, Samuele Marcora, Romain Meeusen, Bart Roelands.
- Poster presentation on 'Biomedical Basis of Elite Performance 2016' in Nottingham, UK, 6-8 March 2016
  Title presentation: *Effects of mental fatigue on cognitive performance and physical endurance in the heat.*
  Jeroen Van Cutsem, Kevin De Pauw, Samuele Marcora, Romain Meeusen, Bart Roelands.
- Oral presentation on 'Science & Cycling 2016' in Caen, France, 29-30 June 2016
  Title presentation: *The impact of mental fatigue on a preloaded cycling-time trial in the heat.*

Jeroen Van Cutsem, Kevin De Pauw, Luk Buyse, Samuele Marcora, Romain Meeusen, Bart Roelands.

- Oral presentation on “Take in move out: over voeding en beweging”, 21st VK Symposium, Gent, 2 december 2016.
  Title presentation: *Mental fatigue impairs sport-specific reaction time.*
  Jeroen Van Cutsem, Kevin De Pauw, Samuele Marcora, Romain Meeusen, Bart Roelands.
- Oral presentation on ‘C4N PhD day’ in Brussels, Belgium, 2 June 2017
  Title presentation: *A caffeine-maltodextrin mouth rinse counters mental fatigue*
  Jeroen Van Cutsem, Kevin De Pauw, Samuele Marcora, Bart Roelands
- Oral presentation on ‘ECSS’ in Metropolis Ruhr, Germany, 5-8 July 2017
  Title presentation: *A caffeine-maltodextrin mouth rinse counters mental fatigue.*
  Jeroen Van Cutsem, Kevin De Pauw, Samuele Marcora, Romain Meeusen, Bart Roelands.
- Oral presentation on ‘C4N PhD day’ in Brussels, Belgium, 8 December 2017
  Title presentation: *Mental fatigue and physical performance*
  Jeroen Van Cutsem, Kevin De Pauw, Samuele Marcora, Bart Roelands
- Oral presentation on ‘ECSS’ in Dublin, Ireland, 4-7 July 2018
  Title presentation: *Faking the heat: subjective thermal strain impairs endurance performance in a temperate environment.*
  Jeroen Van Cutsem, Bart Roelands, Kevin De Pauw, Romain Meeusen, Samuele Marcora

Awards and prizes

- 19th VK Symposium (Vereniging voor Kinesiologie), Antwerp, 12 December 2014.
  - ✓ Winner of the Gaston Beunen-Price for young researchers, best oral presentation of the Symposium.

Technical and professional skills and qualifications

- BrainVision Analyzer 2
  - ✓ BrainVision Analyzer 2 Webinar (#4) - Introduction to spectral analysis with FFT (9/09/2015)
  - ✓ BrainVision Analyzer 2 Webinar (#5) – Artifact handling (12/11/2015)
  - ✓ BrainVision Analyzer 2 Webinar (#6) – Time-frequency analysis with Wavelets: an introduction (17/03/2016)
  - ✓ BrainVision Analyzer 2 Webinar – Introduction to Analyzer 2 & Basics for ERP Analysis (13/10/2016)
- Teaching assistant
  - ✓ Training - Cel Kwaliteitszorg & Onderwijsinnovatie VUB (18/09/2015)
- Statistics
  - ✓ Statistics for PhD researchers (Doctorol School Life Sciences and Medicine; 1/10/2015 – 1/02/2016)
  - ✓ SPSS
- First aid
  - ✓ EHBO basis-course (17/10/2016-18/10/2016-19/10/16)
  - ✓ EHBO refreshment-course (5/10/2017)
  - ✓ EHBO refreshment-course (20/03/2019)