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The effect of mental fatigue on sport-specific physical and technical performance

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DEDICATION

A Paolo, Angela e Niccolò, la mia famiglia,

sempre pronti a supportarmi e a incoraggiarmi in ogni mia scelta.

A Valentina, la mia dolce metà,

sempre al mio fianco in questi anni, capace di seguirmi in ogni mia decisione.

Grazie,

questo traguardo non sarebbe stato possibile senza di voi.

ATTESTATION OF AUTHORSHIP

I hereby declare that the work contained in this thesis has not been previously submitted either in whole or in part to qualify for any other academic award. I also certify that the thesis is my own work carried out during my candidature and that any assistance that I have received in my research work and in the preparation of this thesis has been acknowledged.

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Luca Filipas

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- **Filipas L**, Gallo G, Pollastri L, La Torre A. Mental fatigue impairs time trial performance in sub-elite under 23 cyclists. PloS One. 2019;14(6):e0218405.
- **Filipas L**, Borghi S, La Torre A, Smith MR. Effects of mental fatigue on soccer-specific performance in young players. Medicine & Science in Sports & Exercise. (Under review).
- **Filipas L**, Martin K, Northey J, La Torre A, Keegan R, Rattray B. A 4-weeks endurance training program improves tolerance to mental exertion in untrained individuals. Journal of Science and Medicine in Sport. (Under review).
- **Filipas L**, Ferioli D, La Torre A, Vitale JA. The effects of mental fatigue and sleep deprivation on basketball free throw performance. (In preparation).

Extra publication during candidature

- **Filipas L**, La Torre A, Menaspà P, Giorgi H. Achieving Grand Tour success. A pilot study using cycling's World Tour points. The Journal of Sports Medicine and Physical Fitness. 2017;58(10):1432-1438.
- **Filipas L**, Nerli Ballati E, Bonato M, La Torre A, Piacentini MF. Elite male and female 800-m runners display different pacing strategies during seasons' best performances. International Journal of Sports Physiology and Performance. 2018;13:1344-1348.

- **Filipas L**, La Torre A, Hanley B. Pacing profiles of Olympic and IAAF World Championship long distance runners. Journal of Strength and Conditioning Research. 2018;[Epub ahead of print].

LIST OF CONFERENCE PROCEEDINGS

- **Filipas L**, La Torre A, Menaspà P, Giorgi H. Achieving Grand Tour success - The progression in cycling's World Tour points. Annual Congress SISMES – 2016, Roma – Italy
- **Filipas L**, Tagliabue G, La Torre A, Mottola F. Does mental exertion influence rowing performance in young athletes?. Annual Congress of the European College of Sport Science – 2017, Essen – Germany.
- **Filipas L**, Tagliabue G, La Torre A, Mottola F. Mental fatigue does not influence rowing performance in young athletes. Annual Congress SISMES – 2017, Brescia – Italy
- Riva N, La Torre A, Gallo G, Pollastri L, **Filipas L**. Mental fatigue impairs time-trial performance in Under 23 cyclists. Annual Congress SISMES – 2017, Brescia – Italy
- **Filipas L**, Colnaghi G, La Torre A. Analysis of dropout from high-level alpine ski. Annual Congress SISMES – 2017, Brescia - Italy
- **Filipas L**, La Torre A, Martin K, Keegan R, Rattray B. Improved tolerance to mental exertion after 4 weeks of endurance training. Annual Congress SISMES – 2018, Messina – Italy
- **Filipas L**, La Torre A, Hanley B. Pacing profiles of Olympic and IAAF World Championship long distance runners. Annual Congress SISMES – 2018, Messina – Italy
- Gallo G, Borghi S, La Torre A, **Filipas L**. Effect of mental fatigue on physical and technical performance in young soccer players. Annual Congress SISMES – 2018, Messina – Italy
- **Filipas L**, Martin K, Northey J, La Torre A, Keegan R, Rattray B. A 4-week endurance training program improves tolerance to mental exertion in untrained individuals. Annual Congress of the European College of Sport Science – 2019, Prague – Czech Republic

- **Filipas L**. The effect of mental fatigue on endurance sports. Annual Congress of the Action Sports & Exercise Medicine – 2019, Malcesine – Italy
- **Filipas L**, La Torre A, Ferioli D, Vitale JA. The effects of mental fatigue and sleep deprivation on free throw basketball performance. Annual Congress SISMES – 2019, Bologna – Italy

ABSTRACT

Introduction: Acute mental fatigue is defined as a psychobiological state that may arise during or after prolonged cognitive activities. Despite several studies showed that mental fatigue appears to impair sport performance, the scientific comprehension of this topic is still limited. Therefore, the aim of this thesis is to broaden the knowledge on the effects of mental fatigue on the sport-related performance.

Study 1: This study aimed to investigate the effect of mentally demanding cognitive tasks on rowing performance in prepubertal athletes. Seventeen young rowers completed three separate testing sessions during which they performed three different cognitive tasks before completing a 1500 m time trial on the rowing ergometer. In the two experimental conditions, one hour of a standard cognitive task (Stroop task) and an arithmetic school test were used to elicit mental effort; in the control condition a time-matched, not demanding activity was carried out (painting). The performance of the time trial did not differ between conditions; physiological and perceptual measures recorded during the physical task were not affected by the conditions.

Study 2: This study investigated the effect of a mentally demanding response inhibitory task on time trial performance in sub-elite under 23 cyclists. Ten under 23 road cyclists completed two separate testing sessions during which they performed two different cognitive tasks before completing a 30-min time trial on the cycle ergometer. In the experimental condition, 30 min of a standard cognitive task (Stroop task) was used to elicit mental fatigue; in the control condition, a non-demanding activity was carried out. Mean power output and cadence were negatively affected by the Stroop task, while heart rate (HR), rating of perceived exertion (RPE), blood lactate concentration, and heart rate variability (HRV) did not differ between the two conditions.

Study 3: This investigation examined the effects of mental fatigue on soccer-specific physical and technical performance in young players. Twelve under-14 (U14), twelve under-16 (U16) and twelve under-18 (U18) soccer players completed the two parts of the investigation. Part one assessed the soccer-specific physical performance using the Yo-Yo Intermittent Recovery Test, Level 1 (Yo-Yo IR1). Part two assessed the soccer-specific technical performance using the Loughborough Soccer Passing and Shooting Tests (LSPT, LSST). Each part was preceded by 30 min of Stroop task (mentally fatiguing task) or 15 min of reading magazines (control task) performed in a randomised and counterbalanced order. Mental fatigue significantly reduced Yo-Yo IR1 distance in the three age groups, alongside an increase in HR and RPE. Mental fatigue reduced soccer-specific physical performance in U14, U16 and U18 players, without alteration of technical performance, except for LSPT in U18.

Study 4: This study investigated whether 4 weeks of endurance training could improve tolerance to mental exertion in untrained participants. Twenty participants completed a 4-week training protocol in a randomised and counterbalanced order. Baseline and follow-up assessment were conducted over three sessions in the week preceding and following the training period. During session 1, participants completed an incremental maximal ramp test. During sessions 2 and 3 participants completed a 15 min cycling time trial preceded by either a mental exertion or control task (counterbalanced). Following baseline assessments, participants were randomised into a physical training or placebo group that completed the training intervention thrice weekly over four weeks. The physical training resulted in increases in peak oxygen consumption (VO_{2peak}) relative to the placebo group. Physical training group increased their time trial distance following the mental exertion task to a greater extent than the placebo group. RPE during the time trial and perceptual measures of mental exertion did not significantly change between groups.

Conclusions: This thesis provides insight into the effects of mental fatigue on sport-specific physical and technical performance, focusing in broaden the knowledge on different age-groups

and evaluating, for the first time, the effect of an endurance training protocol on the ability to tolerate mental fatigue.

KEYWORDS

Mental fatigue

Cognitive fatigue

Endurance performance

Technical performance

Perception of effort

Tolerance to fatigue

Psychophysiology

Psychobiology

LIST OF ABBREVIATIONS

BRUMS	Brunel mood scale
CI	Confidence interval
ERN	Event-related negativity
ES	Effect size
HR	Heart rate
HRV	Heart rate variability
IES	Inverse efficiency score
LSPT	Loughborough Soccer Passing Test
LSST	Loughborough Soccer Shooting Test
NASA-TLX	NASA task load index
RMSSD	Root mean square of successive differences between adjacent R-R intervals
RPE	Rating of perceived exertion
RT	Response time
SD	Standard deviation
U14	Under-14
U16	Under-16
U18	Under-18
VAS	Visual analogue scale
VO_{2max}	Maximal oxygen uptake
VO_{2peak}	Peak oxygen uptake
Yo-Yo IR1	Yo-Yo Intermittent Recovery Test, Level 1

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CHAPTER ONE

Introduction

Background

Fatigue is traditionally described as "severe fatigue arising from mental or physical exercise or disease" and/or "decrease in muscle or organ effectiveness following extended exercise". When fatigue is part of a prolonged involvement in a physical task, the function of physiological systems can be changed. Traditionally, exercise science literature classifies exercise-induced reduction in maximum strength output as neuromuscular or muscle exhaustion (Gandevia, 2001). Decreased force production capacity of the muscle group (i.e. muscle fatigue) has been shown to impair endurance performance and motor skills both in the laboratory and on the field (Apriantono et al., 2006; De Morree and Marcora, 2013; Enoka, 1995; Enoka and Duchateau, 2008; Marcora et al., 2008; Missenard et al., 2009). These changes in physical performance were ascribed to both central (i.e., a progressive decrease in the voluntary activation of muscle during practice; Gandevia, 2001) and peripheral (i.e. changes at or distal to the neuromuscular junction; Allen et al., 2008) alterations in neuromuscular function.

When fatigue is induced by prolonged engagement in mental exertion, fatigue is traditionally defined as mental fatigue (e.g., Boksem and Tops, 2008; MacMahon et al., 2014; Marcora et al., 2009; Wang et al., 2016). Mental fatigue is a psychobiological state caused by prolonged demanding cognitive activities. It can be characterized by an increase in feelings of tiredness or even exhaustion, an aversion to continue the ongoing task, and a decrease in cognitive performance (Boksem and Tops, 2008; Boksem et al., 2006). Mental fatigue can be experienced physiologically, subjectively and behaviourally (van Cutsem et al., 2017). Altered parasympathetic (Mizuno et al., 2011) and brain activity (Brownsberger et al., 2013; Wang et al., 2016), lack of energy (Boksem and Tops, 2008) and decreased response accuracy (Barch et al., 1997), among others, are some of the consequences of mental fatigue.

While the effects of mental fatigue on cognitive performance have been widely investigated (Boksem et al., 2006; Lorist, 2008; Lorist et al., 2005; van der Linden and Eling, 2006; van der

Linden et al., 2003; van der Linden et al., 2006), the interest of researchers in investigating a potential impact of mental fatigue on physical performance remains relatively new. Mosso was the first in 1906 to report a decreased muscle endurance performance in two colleague professors after several lectures and oral examinations (Mosso, 1906). For more than one century scientist forgot this topic focusing only on the physical fatigue. Finally, in 2009, Marcora and colleagues confirmed a negative impact of mental fatigue on physical performance in humans (Marcora et al., 2009). Since the study of Marcora and colleagues (Marcora et al., 2009), several studies from different research groups investigating the effects of mental fatigue on physical performance have been published. In chapter two of this thesis, all the studies published analysing this topic have been reported.

Recently, an unpublished meta-analysis on this topic have questioned the real impact of mental fatigue on exercise performance (Holgado et al., 2019). Therefore, at the starting point of this research project it became crucial to expand the knowledge of this topic, evaluating the effect of mental fatigue in different age-groups. Throughout school days young athletes are engaged in mentally demanding activities such as classes, exams and homework that they alternate with training sessions and/or competitions. Therefore, it would be relevant for these athletes establishing the impact of activities that require mental effort on their physical performance. Moreover, performance at school and adjusting training due to school commitments have been cited as potential factors leading to burnout among junior tennis players (Gould et al., 1996) and golfers (Cohn, 1990). Studying the relationship between acute mental fatigue and physical performance in young athletes could promote adequate strategies for reducing mental fatigue in young athletes. Furthermore, no chronic studies that evaluated the effect of an endurance training protocol on the ability to tolerate mental fatigue have been published.

Thesis aim

The aim of this thesis is to broaden the knowledge on the effects of mental fatigue on sport-specific physical and technical performance, focusing on possible age-specific differences. Study 1 examines the effect of mentally demanding cognitive tasks on rowing performance in prepubertal athletes. Study 2 investigates the effects of mental fatigue on performance in a specific age-group of cycling, the under 23. Study 3 compares the effects of a mentally fatiguing task on soccer-specific physical and technical performance in three different age-groups. Study 4 explores the effects of 4 weeks of cycling endurance training on the ability of untrained individuals to tolerate mental fatigue.

CHAPTER TWO

Review of the literature

Literature search

A literature search has been carried out on 1 September 2019 in Pubmed, Medline, Scopus and Web of Science using the following terms and Boolean operators: “mental fatigue” or “cognitive fatigue” or “mental exertion” and “physical performance” or “exercise” or “muscle fatigue” or “sport”.

Searches were limited to papers published in English until September 2019. The reference lists of the retrieved studies were also reviewed to find additional studies that might not have appeared in the databases with our search terms. The purpose of this review is to give a general understanding on the existing literature on mental fatigue and physical performance, not to describe each article to the smallest detail.

Inclusion and exclusion criteria

The following inclusion criteria were considered for this review: publication available in English; controlled trials; cognitive task prior to a physical exercise; the main outcome was a measure of exercise. Studies were excluded following these criteria: participants were symptomatic or in poor health condition; articles were not published in a peer-reviewed journal.

Figure 2.1 summarizes the study selection process. The initial search returned 2436 publications. After identifying 465 duplicate articles, 145 articles were selected for inspection on the basis of their title and/or abstract. Seventy-five full articles were assessed for eligibility and 39 were included in the analysis, divided in 28 articles on endurance performance, 7 on force production and 11 on sport-specific technical performance (with 7 articles included in two of these sections).

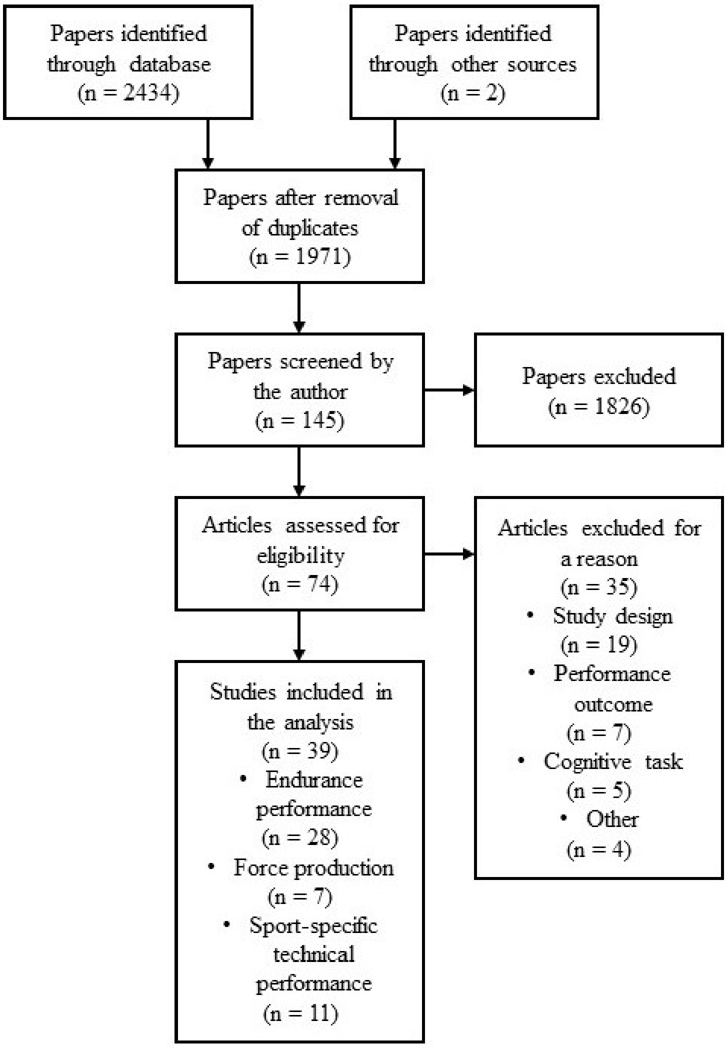

Figure 2.1. Summary of the study selection process

Mental fatigue and endurance performance

Endurance can be defined as the ability to withstand stress over prolonged periods of time. An endurance sport is therefore any sport in which there is a prolonged physical stress. Traditionally, endurance performance refers to a submaximal exercise soliciting mainly the aerobic energy system. Therefore, only studies involving exercise lasting at least 75 s were included (Gastin, 2001). Table 2.1 summarize the literature on the effects of mental on endurance performance, investigated as constant-load exercise, incremental exercise or self-paced exercise. The first investigations seemed to show that mental fatigue can negatively alter endurance performance independently to the discipline and the type of exercise (Marcora et al., 2009; Pageaux et al., 2013; MacMahon et al., 2014). Recently, few studies (Clark et al., 2019; Filipas et al., 2018; Vrijkotte et al., 2018) seems to tone down the amount of the impairment, showing that, in some cases, performance is not reduced after a prolonged cognitive task. In total, 9 investigations (out of 31) report no changes in performance after a mental fatiguing task. An explanation of these controversial results is not fully possible, given that the physiological mechanism of action of mental fatigue has been just hypothesized. As proposed by Martin and colleagues (Martin et al., 2018), a plausible explanation for the negative impact of mental fatigue on endurance performance is that prolonged mental exertion could induce adenosine accumulation in the anterior cingulate cortex, leading to a higher than normal perceived effort during a subsequent endurance exercise. Adenosine is known to accumulate within the brain during periods of wakefulness, before it dissipates with sleep (Porkka-Heiskanen, 1999); it also accumulates during intense physical exercise (Dworak et al., 2007), and likely effortful cognitive activity. This hypothesis finds experimental support in animal studies suggesting that neural activity increases extracellular concentrations of adenosine (Lovatt et al., 2012) and, therefore, impairs endurance performance (Davis et al., 2003). Finally, evidence that caffeine, an antagonist of adenosine, can counteract mental fatigue on endurance performance has been recently found (Azevedo et al., 2016). Despite these preliminary findings seems to suggest a potential link between mental fatigue and brain adenosine accumulation (Martin et al., 2018), this hypothesis still needs to be explored and verified. On the other hand, it is undeniable that the traditional physiological models of exercise cannot explain how mental fatigue impairs endurance performance. Por this purpose, a new “psychobiological” model has been proposed by Marcora and colleagues (Marcora, 2008; Marcora, 2010) to explain this reduction in endurance performance. In this model, an integration of psychological aspects was added to the traditional physiological ones to better explain why mental fatigue can alter physical performance, highlighting the central role of perception of effort in the regulation of endurance performance.

Table 2.1. List of studies investigating the effect of mental fatigue on endurance performance.

References	Subjects	Mental fatigue task	Performance test	Impact of mental fatigue on performance	Impact of mental fatigue on RPE
Azevedo et al., 2016	Recreational (adult)	90 min of AX-continuous performance test	Cycling time to exhaustion at 80 % PPO	↓ performance	↑ RPE
Brown et al., 2019	Recreational (adult)	50 min of AX-continuous performance test	30-min cycling time trial	↓ performance	↑ RPE
Brownsberger et al., 2013	Recreational (adult)	90 min of a computerized decision-making task	2 x 10 min cycling at a fixed RPE (11 and 15)	↓ performance	↑ RPE
Clark IE et al., 2019	Trained (adult)	30 min of different computer-based cognitive tests	6-min cycling at 70 % PPO followed by a cycling time trial	No change	No measures of RPE
Clark IE et al., 2019	Recreational (adult)	30 min of different computer-based cognitive tests	6-min cycling at 70 % PPO followed by a cycling time trial	No change	No measures of RPE
Filipas et al., 2018	Trained (young)	60 min of incongruent Stroop task	1500-m rowing time trial	No change	No change
Filipas et al., 2018	Trained (young)	60 min of arithmetic tests	1500-m rowing time trial	No change	No change
Filipas et al., 2019	Trained (adult)	30 min of incongruent Stroop task	30-min cycling time trial	↓ performance	No change

Franco-Alvarenga et al., 2019	Recreational (adult)	40 min of Rapid Visual Information Processing test	20-km cycling time trial	↓ performance	No change
Head et al., 2016	Recreational (adult)	52 min of a vigilance task	20-min bodyweight resistance training exercise task	No change	No change
MacMahon et al., 2014	Trained (adult)	90 min of AX-continuous performance test	3-km running time trial	↓ performance	↑ RPE
MacMahon et al., 2019	Recreational (adult)	30 min of incongruent Stroop task	Running shuttle test (beep test)	↓ performance	↑ RPE
Marcora et al., 2009	Recreational (adult)	90 min of AX-continuous performance test	Cycling time to exhaustion at 80 % PPO	↓ performance	↑ RPE
Martin et al., 2016	Elite (adult)	30 min of incongruent Stroop task	20-min cycling time trial	No change	No change
Martin et al., 2016	Recreational (adult)	30 min of incongruent Stroop task	20-min cycling time trial	↓ performance	↑ RPE
Otani et al., 2017	Recreational (adult)	90 min of different computer-based cognitive tests	Cycling time to exhaustion at 80 % VO_{2max}	↓ performance	No change
Pageaux et al., 2013	Recreational (adult)	90 min of AX-continuous performance test	20 % knee extensors MVC time to exhaustion	↓ performance	↑ RPE

Pageaux et al., 2014	Recreational (adult)	30 min of incongruent Stroop task	5-km running time trial	↓ performance	↑ RPE
Pageaux et al., 2015	Recreational (adult)	30 min of incongruent Stroop task	6-min cycling at 80 % PPO	No measures of performance	↑ RPE
Penna et al., 2018	Trained (adult)	30 min of incongruent Stroop task	Yo-Yo intermittent recovery test, Level 1	↓ performance	↑ RPE
Penna et al., 2018	Trained (young)	30 min of incongruent Stroop task	1500-m swimming time trial	↓ performance	↑ RPE
Pires et al., 2018	Recreational (adult)	30 min of Rapid Visual Information Processing test	20-km cycling time trial	↓ performance	↑ RPE
Salam et al., 2018	Trained (adult)	30 min of incongruent Stroop task	3 cycling time to exhaustion test at 3 different intensities	↓ performance	↑ RPE
Silva-Cavalcante et al., 2018	Recreational (adult)	90 min of AX-continuous performance test	4-km cycling time trial	No change	No change
Slimani et al., 2018	Trained (young)	30 min of incongruent Stroop task	20-m multistage fitness test	↓ performance	↑ RPE
Smith et al., 2015	Recreational (adult)	90 min of AX-continuous performance test	45-min self-paced intermittent running protocol	↓ performance	↑ RPE

Smith et al., 2016	Trained (adult)	30 min of incongruent Stroop task	Yo-Yo intermittent recovery test, Level 1	↓ performance	↑ RPE
Staiano et al., 2019	Elite (young)	60 min of incongruent Stroop task	2000-m kayaking time trial	↓ performance	↑ RPE
van Cutsem et al., 2017	Trained (adult)	45 min of incongruent Stroop task	45-min cycling at 60 % PPO followed by a cycling time trial (hot environment)	No change	No change
Veness et al., 2017	Elite (adult)	30 min of incongruent Stroop task	Yo-Yo intermittent recovery test, Level 1	↓ performance	↑ RPE
Vrijkotte et al., 2018	Trained (adult)	90 min of incongruent Stroop task	Incremental cycling test	No change	No change

Abbreviations: MVC, maximal voluntary contraction; PPO, peak power output; RPE, rating of perceived exertion. An increase in perception of effort is highlighted in two possible ways: increase in RPE at a fixed workload, or same RPE associated with a reduction in workload in the context of self-paced exercise.

Mental fatigue and force production

Force production refers to the ability of an athlete to produce a high force, power or speed for a short duration during. Table 2.2 summarize the literature on the effects of mental on force production, investigated in isolated or whole-body exercises. The results show that exist strong experimental evidences that mental fatigue does not reduce the ability of an athlete to produce maximal levels of force, both in isolated and whole-body exercises (in 6 out 7 articles). This fact is unsurprising, given the marginal role of perception of effort in the regulation of maximal and all-out exercises. This fact gives us a better understanding in why just 7 papers has been published on this topic. Furthermore, one of these studies (Pageaux et al., 2015) showed that maximal force production was not decreased to a greater extent in the presence of mental fatigue, reinforcing the fact that that mental fatigue and central fatigue are two distinct phenomena.

Mental fatigue and sport-specific technical performance

Motor skills performance refers to the ability of an athlete to perform goal-directed movements during isolated or whole-body exercise. Studies included Table 2.3 include measurement of goal-directed movements in the field. Motor control is traditionally investigated with testing involving the completion of specific sport-technical tasks. The results show that exist full experimental evidences that mental fatigue reduces the ability of an athlete to perform in sport-specific technical skills. The physiological explanation for this result is unknown yet, but may be attributed to an increment in distractibility, difficulty in sustaining attention and ignoring irrelevant information (Boksem et al., 2005). Another possibility lies in the lower testosterone levels after mental fatigue compared to a control condition found in a recent study (Moreira et al., 2018). This might affect dopaminergic transmission to brain areas concerned with cognitive control, that ultimately could result in individual increased technical errors.

Table 2.2. List of studies investigating the effect of mental fatigue on force production.

References	Subjects	Mental fatigue task	Performance test	Impact of mental fatigue on force production
Budini et al., 2014	Recreational (adult)	100 min of a switch task test	Knee extensors MVC	↓ force production
Duncan et al., 2015	Recreational (adult)	40 min of a vigilance task	4 x 30 s Wingate cycling test	No change
Le Mansec et al., 2018	Trained (adult)	90 min of AX-continuous performance test	Elbow flexors MVC	No change
Martin et al., 2015	Recreational (adult)	90 min of AX-continuous performance test	3min all out cycling test, CMJ, knee extensors MVC	No change
Pageaux et al., 2013	Recreational (adult)	90 min of AX-continuous performance test	Knee extensors MVC	No change
Pageaux et al., 2015	Recreational (adult)	30 min of incongruent Stroop task	Knee extensors MVC	No change
Smith et al., 2015	Recreational (adult)	90 min of AX-continuous performance test	45-min self-paced intermittent running protocol	No change

Abbreviations: CMJ, counter movement jump; MVC, maximal voluntary contraction.

Table 2.3. List of studies investigating the effect of mental fatigue on sport-specific technical performance.

References	Subjects	Mental fatigue task	Performance test	Impact of mental fatigue on sport-specific technical performance
Badin et al., 2016	Recreational (adult)	30 min of incongruent Stroop task	Small-sided game (video analysis of technical variables)	↓ performance
Coutinho et al., 2018	Recreational (young)	30 min of incongruent Stroop task	Small-sided game (video analysis of tactical variables)	↓ performance
Le Mansec et al., 2018	Trained (adult)	90 min of AX-continuous performance test	Table tennis performance test	↓ performance
Moreira et al., 2018	Trained (adult)	30 min of incongruent Stroop task	Small-sided game (video analysis of technical variables)	↓ performance
Smith et al., 2016	Trained (adult)	30 min of incongruent Stroop task	Loughborough Soccer Passing Test and Shooting Test	↓ performance
Smith et al., 2016	Trained (adult)	30 min of incongruent Stroop task	Soccer-specific decision-making task	↓ performance
Smith et al., 2017	Trained (adult)	30 min of incongruent Stroop task	Loughborough Soccer Passing Test	↓ performance

Veness et al., 2017	Elite (adult)	30 min of incongruent Stroop task	Cricket-run-two test	↓ performance

Induction of mental fatigue

As previously reported in our revision of the literature, mental fatigue is induced in laboratory by prolonged engagement in demanding cognitive tasks. A huge number of manuscripts uses the Stroop task (Stroop, 1992) or the AX Continuous Performance test (Carter et al., 1998) as a task to induce mental fatigue (Van Cutsem et al., 2017). However, any cognitive tasks involving sustained attention, working memory, and response inhibition could be implemented as a mental fatigue tool. But we must acknowledge that, despite these tasks involve specific executive functions that are also involved in training sessions and competitions, an ecological improvement of the task is necessary. In this direction, looking at our study in preparation, we tried to implement a mental fatigue task that may occur during a competition (i.e., a technical basketball video).

CHAPTER THREE

The effect of mentally demanding cognitive tasks on rowing performance in young athletes

Filipas L, Mottola F, Tagliabue G, La Torre A. The effect of mentally demanding cognitive tasks on rowing performance in young athletes. Psychology of Sport & Exercise. 2018;39:52-62.

Abstract

Objectives: The present study aims to investigate the effect of mentally demanding cognitive tasks on rowing performance in prepubertal athletes. **Design:** Randomised, counterbalanced and crossover. **Method:** Seventeen rowers, aged between 10 and 12 years, completed three separate testing sessions during which they performed three different cognitive tasks before completing a 1500 m time trial on the rowing ergometer. In the two experimental conditions, one hour of a standard cognitive task (Stroop task) and an arithmetic school test were used to elicit mental effort; in the control condition a time-matched, not demanding activity was carried out (painting). Subjective workload and mood were measured before and after the treatments, and the motivation was recorded before the time-trial. During the time trial, time, power, speed, cadence, HR and RPE were assessed. **Results:** The Stroop task and the arithmetic test were rated more mentally demanding ($p < 0.001$), effortful ($p < 0.001$) and frustrating ($p = 0.001$) than the control task, but the items fatigue ($p = 0.437$, $p = 0.197$) and vigour ($p = 0.143$, $p = 1.000$) after the cognitive tasks were not significantly different from the control. The performance of the time trial did not differ between conditions (time: $p = 0.521$; power: $p = 0.208$; speed: $p = 0.341$); physiological ($p = 0.556$) and perceptual ($p = 0.864$) measures recorded during the physical task were not affected by the conditions. Accordingly, pacing profiles ($p = 0.312$) and cadence ($p = 0.062$) did not differ between the conditions. **Conclusions:** Mentally demanding activities did not affect the subsequent physical performance in prepubertal athletes.

Introduction

Acute mental fatigue is defined as a psychobiological state that may arise during or after prolonged cognitive activities and is characterized by the feelings of tiredness or even exhaustion, a decreased commitment and increased aversion to continue the current activity (Boksem and Tops, 2008). It has been shown that acute mental fatigue has a detrimental effect on cognitive performance (Lorist et al., 2005; van der Linden et al., 2003) and in other performance settings, such as driving (Craig, 2001) and physical performance (van Cutsem et al., 2017).

Different studies reported that mental fatigue induced with prolonged cognitive tasks impaired the subsequent performance of constant load (Marcora et al., 2009), self-paced (Brownsberger et al., 2013) and intermittent (Smith et al., 2015) endurance tasks. These findings were replicated in different whole-body exercises, i.e. cycling (Martin et al., 2016) and running (MacMahon et al., 2014; Pageaux et al., 2014). In addition, research reported impairment in the performance of local muscular exercise (Pageaux et al., 2013) and isometric endurance handgrip (Bray et al., 2008; Graham and Bray, 2015) that followed demanding cognitive tasks. Recently, the detrimental carryover effect of mental fatigue has been extended to whole-body resistance exercises (Graham et al., 2017; Head et al., 2016) and soccer-specific physical performance (Smith et al., 2016).

The studies associated the decline in the endurance performance with an increased RPE during exercise at constant load or a decreased workload/rate of perceived exertion ratio during self-paced exercise. On the contrary, the cognitive tasks did not affect the physiological variables commonly associated with endurance performance (i.e. HR, cardiac output, oxygen consumption) (see van Cutsem et al., 2017). However, it still under debate whether mental exertion could alter the neuromuscular functions during the physical task that follows. In this regard, Bray et al. (Bray et al., 2008) reported that muscular activation assessed with the electromyography during an isometric submaximal contraction was increased after an ego-depletion task compared to the control condition. On the same line, Pageaux, Marcora, Rozand and Lepers (Pageaux et al., 2015) found a higher electromyography of the vastus lateralis during a whole-body cycling task following a mentally demanding task compared to the control condition. Conversely, it seems that mental exertion did not impair maximal muscular activation on a maximal strength task (Rozand et al., 2014) nor affect the decline of maximal muscular activation induced by the endurance task (Pageaux et al., 2015). The last results indicated that the mental effort did not increase the development of central fatigue induced by physical exercise, though it may influence motor control (Pageaux et al., 2015).

Most of the studies mentioned above involved recreational or well-trained athletes. Interestingly, Martin et al. (Martin et al., 2016) suggested that training history and performance level may interact with the effect of mental fatigue. Specifically, they compared the effect of mental fatigue on the following endurance performance in recreational and in elite cyclists. Their results showed that working for 30 min on a modified Stroop task diminished the performance in the recreational cyclist's group, while it did not affect the time trial of the elite athletes. Also, they reported that elite cyclists performed faster during the Stroop task then recreational, suggesting a potential association between resistance to mental fatigue and increased inhibitory control in professional cyclists. In accordance with that, it has been shown that faster ultra-endurance runners were better than the slower group in inhibiting the motor response (go-no go trials) and suppressing interference in a dual-task paradigm (Cona et al., 2015). These preliminary findings suggested that inhibitory control may be crucial for the success of the endurance athletes. However, it is unknown whether this characteristic is genetic or acquired through experiences.

Inhibitory control is part of the executive functions constituting the higher cognitive processes involved in the control of goal-directed behaviors, and it refers to the ability to overcome the preponderant response to guide behavior toward the task goal. Behavioral studies showed that although infants are able to suppress the more automatic response to generate appropriate task responses, the rate of inhibition improved across childhood until late adolescence. Hence, the neural mechanism underlined response inhibition are available early in the development, but the systems and the processes are less efficient and slower in children compared to adults (Luna et al., 2010). Consequently, it is possible that children may exert further effort to perform the same task compared to adults. However, prolonged cognitive performance in children has received little attention and to our best knowledge, the only published article that evaluated the effect of mental fatigue in healthy children dated back to 1912 (Winch, 1912; Winch, 1912).

Throughout school days young athletes are engaged in mentally demanding activities such as classes, exams and homework that they alternate with training sessions and/or competitions. Therefore, it would be relevant for these athletes establishing the impact of activities that require mental effort on their physical performance. Furthermore, performance at school and adjusting training to school have been cited as potential factors leading to burnout among junior tennis player (Gould et al., 1996) and golfer (Cohn, 1990). Hence, the study of the relationship between acute mental fatigue and physical performance in young athletes could promote adequate strategies to monitor fatigue and foster a positive young athlete’s development.

Based on the results reported by Martin and colleagues (Martin et al., 2016), investigations on the effect of mentally demanding tasks on the physical performance of prepubertal athletes could also provide additional information on when elite athletes’ performance becomes less sensitive to prior mental effort offering future perspectives for talent identification and young athletes’ development plans. Moreover, the interplay between mental and physical effort in children could also give an insight into the reciprocal effect of physical activity and cognitive performance.

Because of the large number of researches attesting that mental fatigue impaired endurance performance in adults, the main aim of this exploratory study was to test whether this effect extended to the rowing performance of prepubertal children. At this age, the neural system and processes underlying inhibitory control are still immature. Hence, we hypothesised that working on demanding cognitive tasks known to elicit response inhibition would increase the feeling of fatigue and negatively affect the subsequent endurance performance compared to the control condition where a low demanding task was carried out.

The second aim of the study was to compare the effect of a standard computerised cognitive task as used by previous research (van Cutsem et al., 2017) with everyday cognitive activities (i.e. homework, or exams) to assess whether the possible detrimental effect extended to more applied tasks.

Methods

Subjects

Eighteen young rowers (11 males and six females, 11 ± 1.06 year, 46.72 ± 11.14 kg, 154.79 ± 9.41 cm, > 2 training sessions per week, 1.5 ± 0.85 years of rowing experience) voluntarily participated in this study. All participants were recruited from a local rowing club affiliated to the Italian Rowing Federation. The required sample size was based on the effect of cognitive tasks on physical performance reported by previous studies using a within-subject design and a time trial as a physical task (MacMahon et al., 2014; Martin et al., 2016; Pageaux et al., 2014). The studies reported a large effect size (ES), $\eta^2p = 0.31$ to 0.683. The priori sample size calculation (G*Power version 3.1.9.2) with $F(v) = 0.73$, $\alpha = 0.05$, power = 0.80 indicated that a sample of 18 would be sufficient for the analysis. One subject did not meet the inclusion, and 17 subjects were included in the final analysis.

The athletes have regularly been involved in rowing training and competition for at least 6 months; during the three months preceding the data collection and throughout the period of the study subjects performed three to five training sessions per week of about 90 min, at least two of them were rowing-specific (on the rowing ergometer or outdoor) and one involved strength training. Eligibility criteria were as follows: aged 10 to 14 year, free from any known medical diseases, injuries, colour vision deficiencies and learning disorders, free from any medication. Parental consent was provided for all participants (subjects younger than 18 years), and procedures set by the university ethics committee for dealing with minors were followed. The study design and procedures were approved by the local research ethics committee of the University of Milan and followed the ethical principles for medical research involving human subjects set by the World Medical Association Declaration of Helsinki. Participants and their parents were not informed about the real aim of the study; however, they were provided with written instructions outlining all the procedures involved in the study.

Experimental design

A randomised counterbalanced cross-over design was used for the experimental component of the present study which involved three separate testing sessions. In two visits, they either performed one hr of a computerised cognitive task (Stroop task), or they worked on a customised standard school exam for the same duration. A third condition during which subjects performed a low demanding cognitive activity (painting Mandala) was used as a control. Physical performance was assessed with a 1500 m rowing ergometer time trial. The order of the experimental treatments (intervention 1; intervention 2; control) was randomly allocated based on uniformly balanced permutations (123/132/213/321/231/312) generated by a web-based computer program (www.randomization.com).

Experimental procedures

Subjects were tested individually on four different occasions. The visits were completed at the local gym where athletes used to train. The tests were performed within the training hours of the clubs when the access to the gym was limited to the athletes and their coach to maintain similar external conditions between the sessions. All procedures were carried out in an isolated room with standard environmental conditions (i.e. temperature: 18 ± 1 °C) located on the second floor of the structure where only the participant and the researchers could access.

Preliminary sessions. During visit one, participants weight and height were measured, thereafter they were familiarised with the tests and measures to be used for the experimental sessions, i.e. Stroop task (for the time needed to reach a minimum of 90 % of accuracy), the psychological questionnaires and the physical task (subjects were asked to perform the whole-time trial).

Experimental sessions. The experimental visits lasted around 90 min and involved 60 min of either cognitive tasks or a control task (see section "Experimental treatments") followed by the physical task. The sessions entailed the same procedures (Figure 3.1), other than the cognitive task employed (Stroop task, arithmetic test and control). Before and after each cognitive task mood was recorded with the Brunel mood scale (BRUMS). In addition, the subjective workload was measured at the end of the cognitive task with the NASA task load index (NASA-TLX) (see section "Psychological measurement"). Within 10 min after the completion of each respective experimental manipulation, subjects performed the physical task on the rowing ergometer. It involved 3 min of standardised warm-up followed by 1500 m of the time trial (see section "Physical task"). Motivation toward the physical task was assessed right before the starting of the warm-up (see section "Psychological measurement").

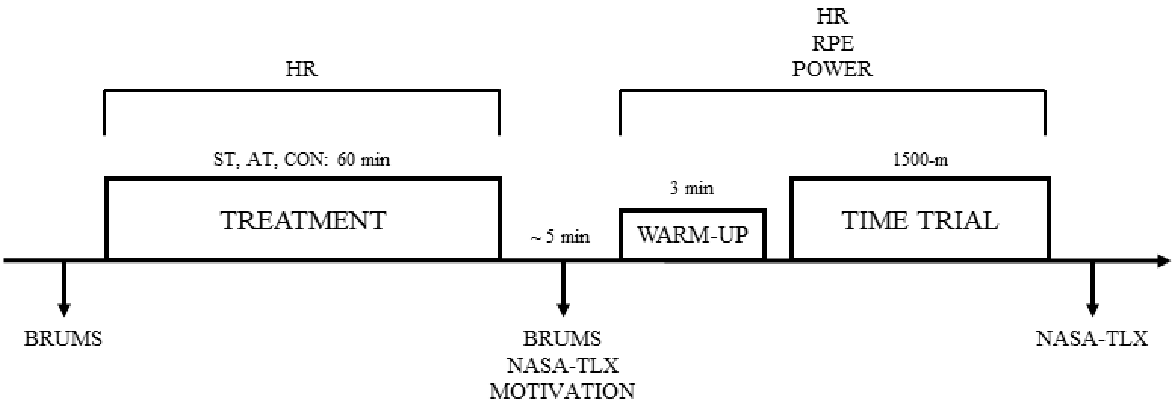

Figure 3.1. Schematic of the experimental visits. HR – Heart Rate; RPE – Rate of Perceived Exertion; ST – Stroop Task; AT – Arithmetic Test; CON – Control.

The experimental visits were separated by seven days and performed on the same day of the week to maintain the mental workload prior to each test as similar as possible. Each participant carried out the visits individually and at the same time of day (within one hr period). Sessions starting times ranged from 14:00 to 18:00 among participants. Before each session, all participants received the instructions to sleep at least seven hours and to drink 35 $mL \cdot kg^{-1}$ of body weight within the 24 hours before the sessions. Moreover, they were required to refrain from homework or others cognitive activities and to avoid caffeine within the 2 hours before the visits and to eat a light meal one hour before the experimental sessions maintaining the meal consistent among the three visits. They were also asked to declare if they had taken any medications or had any injuries or illness. Full compliance with instructions was observed prior to testing sessions.

Experimental treatments

Intervention 1 – Stroop task

Participants performed a 60 min modified incongruent Stroop colour-word task. The Stroop task demands response inhibition and sustained attention (MacLeod and MacDonald, 2000) and has been employed by previous research on the same topic (Pageaux et al., 2014; Smith et al. 2016). Four words (red, blue, green, and yellow) were randomly displayed one at a time on a computer screen. Participants were required to press one of four coloured buttons on the keyboard (red, blue, green, and yellow), with the correct response corresponding to the ink colour of the word (red, blue, green, and yellow), rather than the word's meaning. Therefore, if the word *yellow* was written in blue ink, the correct response was *blue*. The words presented, and their ink colours were randomly generated and selected by computer software, E-Prime

(Psychology Software Tools Inc., Pittsburgh, PA) and were 100 % incongruent. Words appeared centrally on a white background in 24-point uppercase Helvetica and lasted until subject gave a response. Subjects were instructed to respond as quickly and accurately as possible. Visual feedback was provided after each trial in the form of correct or incorrect response, reaction time and accuracy so far. Participants were familiarised with the Stroop task during the preliminary visit and performed 24 practice attempts prior to the experimental task to ensure they fully understood the instruction and to reduce the learning effect on performance. The total number of correct responses for the entire 60 min Stroop task were calculated and the reaction time of the correct responses and accuracy (percentage of correct responses) were averaged for six blocks of 10 min during the 60 min Stroop task. In addition, the inverse efficiency score (IES) were calculated for the entire 60 min Stroop task The IES provides a measure for the speed/accuracy trade-off over time on task when accuracy is high (i.e. > 90% of correct responses). The index is computed by dividing the mean reaction time by the proportion of correct response: RT/ PC (Bruyer and Brysbaert, 2011).

Intervention 2 - arithmetic test

Participants performed a 60 min customised arithmetic test. The task was a pencil-paper test involving arithmetic, mathematical and logic exercises taken from the national test, INVALSI, developed by Italian Ministry of Education (Istituto Nazionale per la Valutazione del Sistema Educativo di Istruzione e di Formazione). This test is employed as final grade assessment, and its questions cover the topics studied throughout the year. Seventeen different forms of the test were developed taking arithmetic, mathematical and logic questions from the general test. We provided different questions to each subject so that it was possible to adjust the test based on the individual age and grade and prevent answer suggestions among participants of the same grade. Every form involved blocks of 15 exercises. Blocks were structured similarly within each test and between every individual form and were given to the subject as soon as he completed the previous block. Participants were instructed to respond as accurately as possible to the questions and complete as many exercises as possible in 1 hr period. However, they were asked to leave an exercise blank, if they were not able to solve it. Research staff subsequently scored the test. The score was based on the number of correct responses given. This test was used to compare the fatigue induced by a typical school exam with that of a standard cognitive task. Arithmetic, mathematics and logic exercises were chosen as it has been suggested that mathematics skills rely on executive functions (Cragg and Gilmore, 2014) and more specifically involve response inhibition (Gilmore et al., 2015).

Control condition

The control condition involved performing one hr of a not cognitively demanding task during which participants were asked to paint with a grey pencil to control for the effect of colours on arousal and performance (Elliot and Maier, 2014). Participants were provided with a pre-drawn Mandala, and they were instructed to colour inside the spaces marked with black points. This task was selected because it has been suggested that colouring is a low cognitively demanding but engaging activity that did not entail envisioning and planning (Forkosh and Drake, 2017). Participants were instructed to colour pre-selected part of the Mandala to reduce potential effect of creative processes on mood and affective state.

Physical task

A 1500 m time trial test on the rower-ergometer was used to meet the specific needs of the current investigation. Subjects were instructed to complete the time trial as fast as possible. All tests were performed on the same rowing ergometer (© Concept2 inc, Model D, Morrisville, VT) in the wind resistance mode (a spinning flywheel generates resistance). The distance was chosen to replicate the length of the national races for their age category and their training practice. Before starting the trial, they performed three min of standard self-pace warm-up during which they were instructed to maintain their perceived exertion between 2 and 3 of the

11-points CR10 scale developed by Borg (Borg, 1998). During the time trial, all participants received information about the distance covered at 500, 1000 and by the end of the test at 1250 m. However, they did not receive any feedback about their speed, cadence and HR. No encouragements were provided throughout the trials. Participants reported their perceived exertion using the CR10 at every 150m interval. Moreover, HR was recorded throughout the whole tests (see section "Physiological measurements"). Power output and stroke rate were averaged for the warm-up and every 300 m of time trials. Furthermore, the average speed at every 150 m was calculated to assess the pacing strategy.

Psychological measurements

Rate of perceived exertion

RPE was registered in the last 15 s of the warm-up and every 150 m throughout the time trial with the 11-point CR10 developed by Borg (Borg, 1998). The CR 10 is a category–ratio scale that ranges from 0 (*no effort at all*) to 10 (*maximal effort ever experienced*) with a dot at the end to rate an effort that is higher than the one has ever been experienced. The subjects were asked to rate how heavy and strenuous the exercise felt by looking at the verbal expressions and then giving the number. Before the warm-up participants were given the standard instruction for the scale (Borg, 1998); for example, *3* on the scale is *moderate* it is not especially hard, it feels fine, and it is not a problem to continue exercising, *7* corresponds to *very hard* and strenuous exercise. A healthy person can still go on, but he or she really has to push him or herself. It feels very heavy, and the person is very tired. Also, they were reminded that *10* should correspond to the maximal exertion they have ever experienced in their past training or competitions and that the dot at the end should denote a perceived exertion stronger than *10*, the highest possible level of exertion (Borg, 1998). A copy of the scale was always in full view of the subject. This scale was chosen as the participants were already familiar with it and had been using it for at least three months during their daily training sessions prior to the tests taking place.

Mood

The mood was measured at the beginning of the visit and after the cognitive tasks with the BRUMS validated for adolescents (Terry et al., 1999). The questionnaire consists of 24 items divided into 6 subscales related to mood, Depression, Fatigue, Vigour, Confusion, Anger, Tension. Participants were asked to rate each item on a 5-point Likert scale (*from 0 = not at all, to 4 = extremely*) according to their current mood (*How do you feel right now?*). Each subscale score, with four relevant items, could range from 0 to 16. Fatigue and vigour were used as subjective markers of mental fatigue after cognitive tasks (Marcora et al., 2009).

Motivation

The motivation for the time trials was measured after the warm-up with a single item (*I am motivated to do the time trial*) on a 5-point Likert scale (*0 = not at all, 1 = a little bit, 2 = somewhat, 3 = very much, 4 = extremely*) (Martin et al., 2016).

NASA Training Load Index – subjective workload

The subjective workload was recorded after each intervention and after the physical test with the Italian version of the NASA-TLX (Bracco and Chiorri, 2006). It involves a multi-dimensional rating procedure with 6 domains (Mental demand, Physical demand, Temporal demand, Effort, Frustration). Subjects were asked to rate each of them on a 0 to 20 scale anchored by bipolar descriptors (high/low). Each score was multiplied per 5 so that the final score of each subscale would range from 0 to 100.

Before filling out the questionnaires, athletes were told that they should answer each question based on how they currently felt; there were no right or wrong answers, and they would not be judged on their answers.

Physiological measurements

During the cognitive tasks and the physical tests, HR was recorded with an HR monitor (Polar

M400, © Polar Electro 2016, Oy, Kempele, Finland) and an HR band synchronised with the device. Ten min average and overall mean were used to analyse data of the cognitive task. HR data were collected at every 150 m of the time trials.

Statistical Analysis

All data are presented as mean ± standard deviation (SD). Prior to the analysis, the Shapiro-Wilk's test and the Mauchly's test were employed to test the normality of the data and sphericity assumption respectively. When sphericity was not met, Greenhouse-Geisser correction was used to adjust the significance of the F-ratios. One-way repeated measures ANOVA was used to determine the differences between the three conditions in the time trials performance and in the average HR, power output, cadence and speed during the time trials, in the motivation toward the physical tests and in the subjective workload of the interventions (NASA-TLX). Two-way fully repeated measures ANOVA (3x2) was used to assess the effect of the interventions and time (pre and post interventions) on mood state (fatigue and vigour subscales of the BRUMS). HR during the three interventions was averaged every 10 min and analysed with a two-way fully repeated measures ANOVA (3 x 6) to determine the effect of condition and time. One-way repeated measures ANOVA was used to assess the effect of time on task on the accuracy (% of correct trials) and reaction time during Stroop task. Two-way fully repeated measures ANOVA (3 x 10) was run to define the effect of the interventions and distance (every 150 mt) on the HR, RPE and speed during the trials and 2-way ANOVA (3 x 5) was run for cadence and power during the time trials (i.e. every 300 m distance).

In addition, a mixed 3 x 3 ANOVA with the visits order listed as the between-subject factor and condition as the within-subjects factor was used to exclude a learning effect on the performance and bias in the ratings of the psychological questionnaires after the interventions.

Significant main effects and interactions, when more than two levels were employed, were interpreted through pairwise comparisons with Bonferroni correction. Significance was set at

0.05 (two-tailed) for all analyses, and the ES for each statistical test is reported as partial eta squared (η^2p), using the small = 0.02, medium = 0.13 and large = 0.26 interpretation for ES (Bakeman, 2005). Data analysis was conducted using the Statistical Package for the Social Sciences, version 23 (SPSS Inc., Chicago, IL, USA).

Results

Manipulation check

Average HR was lower during the Stroop task (85 ± 9 bpm) compared with the control condition (91 ± 10 bpm) ($p = 0.038$). However, it did not differ significantly between the arithmetic test (89 ± 11 bpm) and the other conditions (Stroop task: $p = 0.209$; Control: $p = 1.000$). Despite the significant main effect of time on the HR ($F (5, 80) = 5.396$, $p < 0.001$, $\eta^2p = 0.265$), the follow-up tests failed to reveal significant differences between the 5 min blocks.

The analysis of the vigour and fatigue subscales of the BRUMS revealed a main effect of time (vigour: $F (1,16) = 22$, $p < 0.001$, $\eta^2p = 0.580$ and fatigue: $F (1,16) = 20$, $p < 0.001$, $\eta^2p = 0.556$). The fatigue increased over time and the vigour was lower after the interventions compared with baseline. Despite the significant interaction conditions X time (vigour: $F (1.5, 25) = 4.107$, $p = 0.038$, $\eta^2p = 0.204$; fatigue: $F (2, 32) = 4.698$, $p = 0.016$, $\eta^2p = 0.227$), the pairwise comparison of the ratings after the three interventions did not reach the statistical level for significance (vigour: control and Stroop task $p = 0.143$, control and arithmetic test $p = 1.000$, Stroop task and arithmetic test $p = 0.164$; fatigue: control and Stroop task $p = 0.437$ control and arithmetic test $p = 0.197$, Stroop task and arithmetic $p = 0.100$). The main effect of condition was not significant (vigour: $F (1.5, 24) = 2.119$, $p = 0.151$, $\eta^2p = 0.117$; fatigue: $F (1, 20) = 2.821$, $p = 0.102$, $\eta^2p = 0.150$) and the one-way ANOVA of the baseline values did not reveal significant differences among the three conditions, $F (2, 32) = 1.908$, $p = 0.165$ and $F (2, 32) = 0.257$, $p = 0.775$ for the vigour and fatigue respectively.

Thus, the level of fatigue as measured with the BRUMS did not show a significant effect of the two cognitive tasks (data presented in Table 3.1).

Table 3.1. Mood for the three experimental conditions. Data are presented as mean ± SD.

	Mood			
	Vigour		**Fatigue**	
	Pre	**Post**	**Pre**	**Post**
Stroop task	6.7 ± 3.8	4.1 ± 2.6	0.4 ± 1.1	2.5 ± 2.7
Arithmetic test	7.2 ± 3.3	5.1 ± 3.1	0.2 ± 0.4	0.9 ± 0.8
Control	6.2 ± 3.6	5.2 ± 3.4	0.4 ± 0.8	1.5 ± 1.6

On the other hand, the subjective workload assessed after the cognitive tasks using the NASA-TLX showed a main effect of condition for mental demand (F (2, 32) = 22.581, $p < 0.001$, η2p = 0.585), effort (F (2, 32) = 32.740, $p < 0.001$, $\eta^2p = 0.672$), temporal demand (F (2, 32) = 5.118, p = 0.012, $\eta^2p = 0.242$) and frustration (F (1, 21) = 8.911, p = 0.004, $\eta^2p = 0.358$). Pairwise comparisons revealed that mental demand ($p < 0.001$), effort ($p < 0.001$) and frustration (p = 0.001) were higher for both, the Stroop task and the arithmetic test, compared to the control condition, whereas the Stroop task and the arithmetic test conditions did not differ on these items (mental demand and frustration: p = 1.000, effort: p = 0.527). In addition, the temporal demand of the Stroop task was higher than the control task (p = 0.009); while the temporal demand of the arithmetic test did not differ significantly from the Stroop task (p = 0.922) and the control condition (p = 0.214). Physical demand and the performance did not differ between the three conditions (main effect of condition: F (1.5, 25.5) = 1.564, p = 0.229, $\eta^2p = 0.089$ and F (2, 32) = 1.956, p = 0.158, $\eta^2p = 0.109$). Data of subjective workload are reported in Figure 3.2.

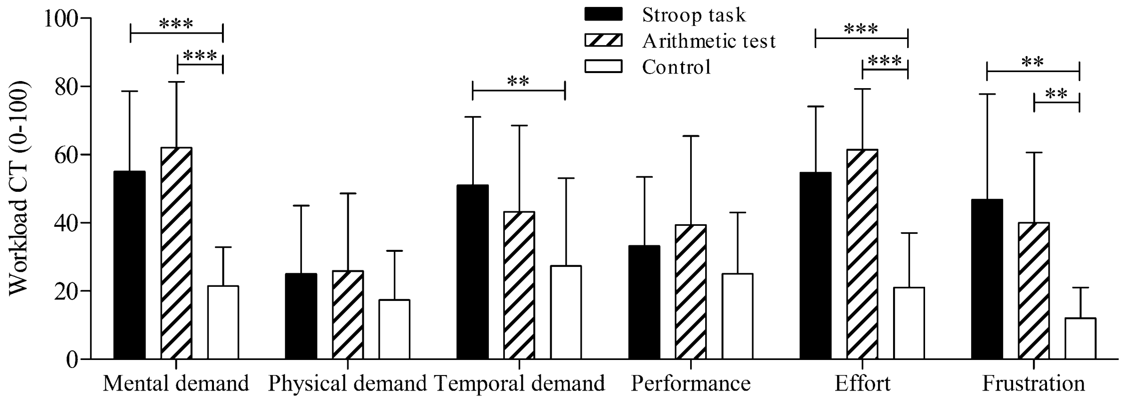

*Figure 3.2. Effect of prior cognitive tasks (CT) on subjective workload measured with NASA-TLX scale. **Significant main effect of condition ($p < 0.01$). ***Significant main effect of condition ($p < 0.001$). Data are presented as mean ± SD.*

The NASA-TLX scales of the time trial did not differ significantly between conditions, apart from the rating of performance that tended to be higher in the arithmetic test condition (performance: F (1.5, 23.5) = 3.847, p = 0.047, mental demand: F (1, 22) = 0.512, p = 0.538, physical demand: F (1, 21) = 0.452, p = 0.559, temporal demand: F (2, 32) = 0.299, p = 0.743, effort: F (2, 32) = 0.700, p = 0.504, and frustration F (2, 32) = 1.318, p = 0.282). The pairwise comparisons did not reveal significant differences between the performance scales (control and Stroop task p = 1.000, control and arithmetic test p = 0.198, Stroop task and arithmetic test p = 0.121).

Values of the motivation were 2.7 ± 0.77, 2.35 ± 0.86, 2.52 ± 0.79 for the control condition, the Stroop task and the arithmetic test condition respectively. A non-parametric Friedman test was used to compare the values of three conditions and rendered a χ^2 (2) = 6.636 which was significant (p = 0.036). However, none of the pairwise comparisons conducted with Bonferroni correction reached the statistical level for significance (control and Stroop task p = 0.435; control and arithmetic test p = 1.000; Stroop task and arithmetic test p = 1.000).

The results of the mixed ANOVA for the order effect on the vigour and fatigue subscales were not statistically significant (between subjects effect for vigour F (5, 11) = 0.315, p = 0.894 and fatigue F (5, 11) = 0.678, p = 0.649 and interaction condition X order for vigour p = 0.786 and fatigue p = 0.676). Similarly, the order did not have a significant effect on the NASA-TLX items (mental demand: F (5, 11) = 1.078, p = 0.423 and F (10, 22) = 0.629, p = 0.773, temporal demand: F (5, 11) = 1.306, p = 0.330, F (10, 22) = 0.791, p = 0.638, effort: F (5, 11) = 0.850, p = 0.543, F (10, 22) = 0.386, p = 0.939 and frustration: F (5, 11) = 2.207, p = 0.127, F (7, 15) = 0.867, p = 0.551, respectively between subject effect and interaction condition X order).

Stroop task performance

Mean response time (RT) and accuracy (percentage of correct responses) for the Stroop task were 794.7 ±127 ms and 0.98 ± 0.01 respectively. Repeated measures ANOVA was used to assess the effect of time on task on the behavioral responses averaged over 10 min period for a total of six blocks. RT tended to increase over time as it was also shown by a decrease in the number of trials performed over the six blocks. Specifically, RT was 759.49 ± 92.56 ms in the first block and 788.88 ± 104.08 ms in the last one. However, the effect of time did not reach the level of statistical significance (F (2, 38) = 2.410, p = 0.094, η^2p = 0.131). On the contrary, accuracy increased significantly with time (F (3, 48) = 6.799, p = 0.001, η^2p = 0.298). Post-hoc tests revealed that accuracy was significantly lower in the first 10 min (mean = 0.96, SD = 0.02) compared with the third 10 min block (mean = 0.977, SD = 0.01, p = 0.045) and the last 10 min block (mean = 0.98, SD = 0.012, p = 0.006). The others comparisons with block 1 were not significant ($p \geq 0.09$), nor were significant the comparisons among all others blocks ($p \geq 0.9$) This trajectory suggested that after the first 10 min the accuracy stabilized and did not change for the remaining period.

Compatible with the trend of the RT, the IES increased slightly but, not significantly over the six blocks (F (2.5, 39.8) = 1.089, p = 0.357, η^2p = 0.064).

Arithmetic test performance

The total number of questions submitted during the arithmetic test was 75.88 ± 32.46. The number of correct answers was 38.38 ± 37.06, with a mean accuracy of 46.35 ± 24.83 %.

Effect of the interventions on time trial performance

The mixed ANOVA to assess the effect of order on the time trial tests was not significant (between-subjects effect F (5, 11) = 0.316, p = 0.893, interaction condition X order (F (10, 22) = 0.931, p = 0.525). This result excluded a carryover effect of the three visits on the performance.

Times to complete the trials were 442.59 ± 63.97 s, 445.29 ± 61.52 s and 446.35 ± 62.30 s for the control condition, the Stroop task and the arithmetic test respectively (Figure 3.3). The performances were not significantly different (F (1.5, 26) = 0.604, p = 0.521, η^2p = 0.036).

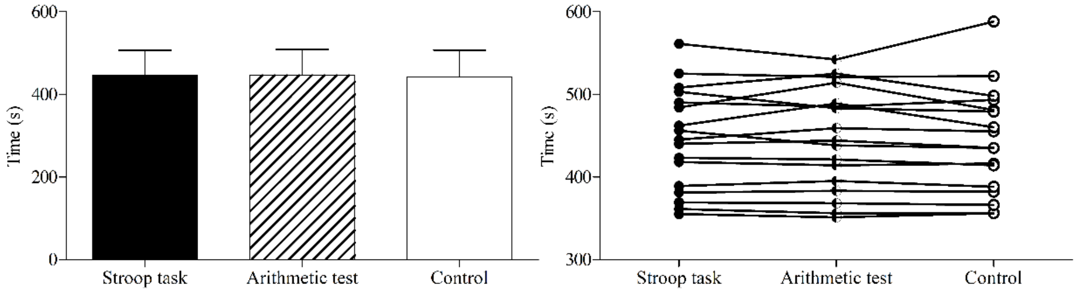

Figure 3.3. Effect of prior cognitive tasks on 1500-m time trial performance. Data are presented as mean ± SD (left) and individual responses (right).

Similarly, average power (F (2, 32) = 1.650, p = 0.208, η^2p = 0.093) and average speed (F (2, 32) = 1.111, p = 0.341, η^2p = 0.065) did not differ significantly and were 121.71 ± 50 W and 12.44 ± 1.76 km·h^{-1} after the control task, 118.94 ± 49.69 W and 12.35 ± 1.72 km·h^{-1} after the Stroop task and 118.92 ± 51.89 W and 12.33 ± 1.77 km·h^{-1} after the arithmetic test respectively. The velocity decreased over the trials (main effect of distance F (1, 21) = 105, p = 0.001, η^2p = 0.868). Post-hoc tests revealed that the speed declined significantly ($p \leq 0.002$) until 1050 m when it remained stable until the end (pairwise comparisons between the last four 150 m splits

$p > 0.05$). The main effect of condition and the interaction condition X distance were not significant (F (2, 32) = 0.917, $p = 0.410$, $\eta^2p = 0.054$ and F (3, 51) = 1.049, $p = 0.382$, $\eta^2p = 0.062$ respectively).

Effect of the interventions on RPE, heart rate, pacing strategy and stroke rate during the time trials

RPE increased significantly over the trial (main effect of distance F (1, 22) = 57.637, $p < 0.001$, $\eta^2p = 0.783$), however, it was not affected by the interventions (main effect of condition F (2, 32) = 0.147, $p = 0.864$, $\eta^2p = 0.009$ and interaction condition X distance F (6, 102) = 0.929, $p = 0.481$, $\eta^2p = 0.055$). Post-hoc tests to describe the main effect of distance showed that the RPE increased significantly until 750 m ($p < 0.005$), it did not differ significantly between 750 and 900 m ($p = 0.086$), 1050 and 1200 m ($p = 0.163$) and 1200 and 1350 m ($p = 0.202$) and it was significantly higher at 1500 m compared to all previous ratings ($p < 0.05$).

Similairly, the HR did not differ significantly between conditions (main effect of condition: F (2, 32) = 0.599, $p = 0.556$, $\eta^2p = 0.038$). It increased significantly over the trial (main effect of distance F (2, 31.5) = 79.66, $p < 0.001$, $\eta^2p = 0.842$) with no significant interaction condition X distance (F (6, 94.5) = 1.451, $p = 0.201$, $\eta^2p = 0.088$). Post-hoc tests for the main effect of distance showed that HR was significantly lower in the first 150 m split compared to the subsequent points ($p < 0.001$); in addition, it differ significantly between 300 ($p \leq 0.001$) and 450 m ($p \leq 0.002$) and all splits following 750 m and between 600 m and all points following 900 m ($p \leq 0.02$) and at 1200 m, 1350 and 1500 m it was significantly higher compared to all previous recordings ($p < 0.05$).

One-way repeated measures ANOVA was run for the final point of RPE and the HR to assess whether the interventions influenced the end-point of the time-trial. However, the analysis did not reveal any significant difference between conditions in the RPE ($p = 0.317$, $\eta^2p = 0.069$) nor in the HR ($p = 0.545$, $\eta^2p = 0.040$). Data of RPE and HR over time are shown in Figure 3.4.

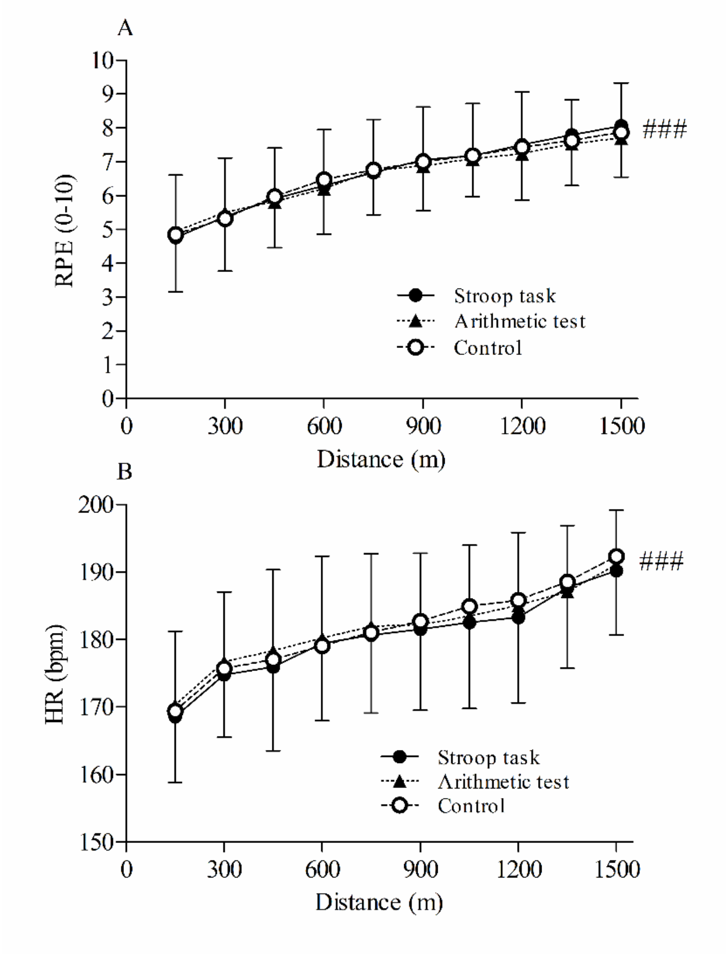

Figure 3.4. Effect of prior cognitive tasks on rating of perceived exertion (RPE; A) and heart rate (HR; B) during the 1500-m time trial. ### Significant main effects of time ($p < 0.001$).

Average speed was obtained from each split times of every 150 m and used to assess pacing profiles of the trial. Before running the analysis to determine any difference between the conditions, a mixed ANOVA (with the order listed as the between-subjects factor) was performed to control the effect of the visits order on the pacing strategy. The results of the analysis were not significant (between-subject effect F (5, 11) = 0.369, p = 0.859, interactions condition X order F (10, 22) = 0.840, p = 0.597, and distance X order F (6, 14) = 0.770, p = 0.616).

Results from the 2-way fully repeated measures ANOVA showed a significant main effect of distance (F (4, 67.5) = 40.321, $p < 0.001$, $\eta^2p = 0.716$) on the average speed of every 150 m splits. The main effect of condition (F (2, 32) = 1.209, p = 0.312, η^2p = 0.070) and the interaction condition X distance were not significant (F (4.5, 72.4) = 1.484, p = 0.210, η^2p = 0.085). Post-hoc tests for the main effect of distance indicated that a reversed J pacing strategy was adopted in all the trials resulting in the first split being the fastest and in a significantly slower speed of all the following 150 m splits ($p < 0.001$). More specifically, the speed decreased significantly from split 2 to the following ones ($p \leq 0.03$) until the last split when it increased to the same value of split 2 (p = 1.000). In addition, it was significantly higher in the 4th split (600 m) compared to the 6th, 7th and 8th (900 to 1200 m) and in the last split compared to the 7th, 8th and 9th (1050 to 1350 m) (Figure 3.5).

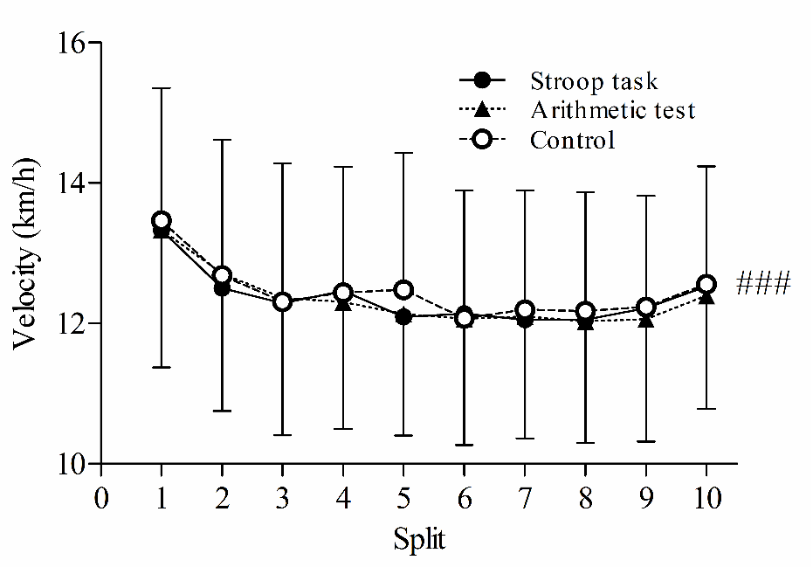

Figure 3.5. Effect of prior cognitive tasks on pacing strategy during the 1500-m time trial. ### Significant main effects of time ($p < 0.001$). Data are presented as mean ± SD.

Average stroke rate was 28.65 ± 3.33, 27.94 ± 2.97, 28.88 ± 3.28 rpm for the control, Stroop task and arithmetic test condition respectively. The main effect of condition (F (2, 32) = 3.038, p = 0.062, η^2p = 0.160) and the interaction condition X distance (F (4, 61) = 0.385, p = 0.811, η^2p = 0.024) were not significant. Post-hoc tests for the main effect of distance (F (1.6, 25.6) = 8.446, p = 0.003, η^2p = 0.345) showed that the stroke rate was higher in the first 300 m split compared to the three subsequent splits ($p < 0.001$, $p = 0.006$, $p = 0.017$) and increased to the same level of the first split in the last 300 m ($p = 1.000$), at this point was also significantly higher than the previous 300 m split ($p = 0.024$).

In the arithmetic test condition, the average stroke rate tended to be higher compared to the Stroop task condition. However, one-way repeated measures ANOVA of the average stroke rate was not significant ($F (2, 32) = 2.728$, $p = 0.081$, $\eta^2p = 0.146$).

Discussion

To our knowledge, this was the first study investigating the effect of mental fatigue on physical performance in a sample of prepubertal athletes. A recent review of the effect of mental fatigue on physical performance reported that acute mental fatigue before exercise performance could negatively affect endurance performance (van Cutsem et al., 2017). In contrast, the main finding of the present study was that prolonged cognitive activities did not affect rowing performance in prepuberal athletes. Accordingly, physiological and perceptual responses during the time trials were not different after the three interventions (Stroop task, arithmetic test and control task).

Self-reported measures were recorded before and after the interventions to assess the state of mental fatigue. From one side, the mood state was similarly affected by the three interventions that resulted in a significant decrease in the vigour and significant increase in the fatigue. Thus, the measures from the BRUMS scale suggested that the two cognitive tasks failed to elicit a significantly different level of fatigue compared to the control activity.

On the other hand, the two cognitive tasks were rated as more mentally demanding, more effortful and more frustrating compared to the control task in the NASA-TLX.

Although these results were divergent in defining whether mental fatigue was effectively induced, similar findings were reported by previous studies (Pageaux et al., 2014; Pageaux et al., 2015). In both studies, the authors employed a modified version of the Stroop task to induce mental fatigue and a congruent version of the same task as a control. None of the two tasks affected the fatigue scale of the BRUMS, while the vigour score decreased similarly after the interventions. However, the ratings of mental demand and effort were significantly higher in the NASA-TLX of the incongruent Stroop task compared to the congruent version and most importantly, the physical performance was impaired after the more effortful and demanding task. Specifically, in the first study, the distance covered during the time trial was significantly shorter following the demanding cognitive task compared to the control (Pageaux et al., 2014); in the second study, RPE measured during six min of constant load test was significantly higher in the incongruent Stroop condition (Pageaux et al., 2015). Their findings suggested that the physical performance may be more sensitive to the subjective experience of effort and/or the perceived demand of the previous cognitive task rather than the state of fatigue assessed with the BRUMS. Martin et al. (Martin et al., 2016) also reported similar findings showing that a different fatigue state did not accompany the reduction in the endurance performance found after the Stroop task when compared to a passive activity. In particular, the fatigue level measured with the four-dimensional mood scale displayed a significant increase in tiredness and a significant reduction in positive energy in both conditions. However, the mental demand and the effort rated on the NASA-TLX were significantly higher after the Stroop.

Based on that, it could be argued that the lack of an effect of the more effortful cognitive tasks in the present study depended at least in part on the fact that the sample tested was different for age or training status to that of previous research.

To our knowledge, only one other study directly investigated the effect of mental fatigue in healthy children (Winch 1912; Winch, 1912). The author looked at the effect of a school day on a memory test performed either in the afternoon or the morning in both 11 and 13 years children. Winch (Winch, 1912; Winch, 1912) reported little differences between the performance of the two groups as well as in the learning effect tested as the improvement in the performance from the preliminary test to the final test. Specifically, in the first experiment involving 45 children aged 13 years old, the average marks were 266 ±34 and 253 ±35.9 (out of 360) for the morning group and afternoon group respectively. In the second experiment, which included 61 boys of 11 years old, the morning group scored 165 ±1.1 and the afternoon group 161 ±1.1 out of 180. The same author suggested that children may be immune to mental fatigue and may be able to learn in the afternoon in the same way as in the morning.

The present results showed that the physical performance of young athletes was less sensitive to mentally demanding tasks compared with that of adult recreational athletes whose performance have been shown to decline after prolonged cognitive tasks (van Cutsem et al., 2017). Hence, it is possible that the children tested were more resistant to mental fatigue because of the age, the training background and fitness level or both.

In the first case, these findings could be explained by the differences in the cognitive processes between adults and children. Behavioral and neuroimaging studies reported that brain areas underlying response inhibition, the frontal lobe, developed between 12 to 17 years and peak around 17 years (Romine and Reynolds, 2005). Over this period, functional neural networks develop and task-specific patterns of activation supporting the cognitive performance increase (Adleman et al., 2002; Rubia et al., 2006). Specifically, Adleman et al., (Adleman et al., 2002) reported increased performance activation of the lateral prefrontal lobe, anterior cingulate and parietal brain regions in young adults compared to children when performing the Stroop task. The decreased activity in the immature systems of children could be interpreted as reduced accessibility to the regions or to the computational abilities that support complex behavior (Luna et al., 2010). This lower activation during cognitive tasks may result in a lower impairment of the cognitive processes when activated over time, similarly to what occurs with exercise-induced peripheral fatigue (Ratel, 2006). The author suggested that children despite being physically less efficient compared to adults, i.e. lower maximal power and maximal aerobic capacity (maximal oxygen uptake, VO_{2max}), display less muscular fatigability because their muscular activation is quantitatively and qualitatively different. In particular, their underdeveloped anaerobic metabolism and the reduced recruitment of fast twitches result in lower accumulation of muscle by-product during high-intensity exercise and higher resistance to muscular fatigue (Ratel, 2006).

Similarly, it could be speculated that the reduced ability to recruit the neural resources during cognitive tasks in the children (Luna et al., 2010) may prevent their full exploitation and result in reduced fatigability over time, although it leads to a worse performance compared with that of adults. However, we are not aware of any study that compared the fatigability of the neural systems in children and adults or investigated the different effect of mental fatigue between adults and children; therefore, further empirical studies are necessary to test this possibility.

A more plausible explanation for the lack of the effect of mental fatigue on the performance could be the involvement of the children in endurance sport. In accordance with that, Martin et al. (Martin et al., 2016) found that elite athletes' performance was not affected by previous mental fatigue and they suggested that elite cyclists could be more resistant to mental fatigue. Our results partly supported this hypothesis suggesting that endurance athletes displayed this characteristic at an early age.

Although they suggested that genetic factors likely support this feature, also the engagement in aerobic exercise and training routine may promote the development of resistance to mental fatigue in endurance athletes.

A growing body of evidence suggested that aerobic fitness (Buck et al., 2008; Scudder et al., 2014) and level of physical activity (Syväoja et al., 2014) are positively associated with the cognitive performance across different executive functions in prepubertal children (see Donnelly et al., 2016 for a review on this topic). These behavioral findings have been corroborated by studies involving the measures of brain structure (Chaddock et al., 2010; Chaddock et al., 2010) and function (Hillman et al., 2009; Hillman et al., 2005; Pontifex et al., 2011). Specifically, Chaddock et al. (Chaddock et al., 2010) showed in two separate studies that children with higher fitness level outperformed their lower fitness peers in a relational memory task and resulted less susceptible to the behavioral interference measured with the Flanker task. The two behavioral outcomes were coupled with a larger volume in the brain structures underlying tasks' performance, namely the hippocampus and the dorsal striatum (nucleus caudate and putamen) for the relational memory and interference control respectively. These results suggested that the relationship between fitness level and cognitive performance may be mediated by direct and selective differences in the brain structure and volume. Studies assessing brain function with electroencephalogram have confirmed the presence of fitness related differences in the cognitive processes sustaining the performance. Specifically, a series of studies reported that children with high fitness level presented larger P3 amplitude signalling greater allocation of attentional resources during stimulus encoding compared to peers with lower fitness level (Hillman et al., 2009, Hillman et al., 2005; Pontifex et al., 2011). In addition to that, the high fitness level group displayed reduced ERN (event-related negativity) amplitude that was interpreted as an increased evaluative threshold to initiate top-down cognitive control as well as greater ERN differences between compatible and incompatible trials that was related to a better ability to modulate cognitive control in response to the stimuli (Pontifex et al., 2011). Further support to the positive effect of exercise on cognitive performance has been provided by empirical studies showing that acute exercise facilitated cognitive performance in preadolescent children (Hillman et al., 2009; Chen et al., 2014).

Altogether, these results indicate that aerobic exercise involves specific cognitive processes that have a potentially positive effect on higher-order brain regions and support the development of cognitive functions across childhood and adolescence. Due to the positive interplay between cognitive functions and aerobic activities young and well-trained endurance athletes may need a low level of effort to sustain prolonged cognitive activities, and this may have reduced the effect of the interventions used to elicit mental fatigue.

In addition, physical activity during school hours is not detrimental to the performance at school (Ahamed et al., 2006) and its benefit may translate into improvement in academic performance (Marques et al., 2017), suggesting that children could adapt positively to the alternation between cognitive demand imposed by school routine and physical demand of structured sport. Based on that, the athletes of the present study could have been well adapted to shift from cognitive and physical activities. Therefore their performance was less sensitive to the intervention. Notably, all but three of them have been involved in rowing for at least one year before starting the experiment and they all have a history of at least four consecutive years of routinely sports practice prior to rowing.

Finally, it could be suggested that endurance athletes are predisposed or trained to endure effort in general. In this regard, fatigue has been defined as an evolutionary emotion that manifests with an increased feeling of effort and is driven by a cost-benefit analysis of the current activity (Boksem and Tops, 2008). The phenomenology of effort would allow disengaging from the task when the cost of acting overcome task reward and this monitoring system would favour efficient goal-directed behavior (Hockey, 2011; Kurzban, 2016). Accordingly, it was shown that increasing the reward during prolonged cognitive task counteracted the detrimental effect of mental fatigue on the cognitive performance and reversed the subjective feeling of effort and aversion to the task (Hopstaken et al., 2015; Hopstaken et al., 2016). Boksem, & Tops (Boksem and Tops, 2008) suggested the presence of a shared neural system that evaluates and regulates mental and physical effort (see also Shenhav et al., 2017) and the detrimental carryover effect of mental fatigue on following physical tasks provided support to this hypothesis. Although research has failed to reveal a reduction in the motivation toward the physical endurance task that followed the cognitive tasks (van Cutsem et al., 2017), studies consistently reported an alteration in RPE during the exercise. The higher perceived exertion during exercise could imply an imbalance in the reward-effort processing elicited by the previous mental effort. Also, Brown & Bray, (Brown and Bray, 2017) recently found that monetary incentives associated with the performance could offset the adverse effect of a short cognitive task on the performance of the subsequent handgrip endurance test, showing that task reward could affect the relationship between mental fatigue and physical performance. Inzlicht, Shenhav, & Olivola (Inzlicht et al., 2018) suggested that *effort,* although commonly considered as inherently costly, could also add value to an activity or be a value itself through learned industriousness or need for cognition. Consequently, it could be argued that the young athletes tested in the present study, as well as the elite sample tested by Martin et al. (Martin et al., 2016), may perceive the physical task as rewarding per se because its conditioned association with incentives (success, money) and/or individual predisposition to engage in effortful activity. According to the opportunity-cost model of mental effort (Kurzban et al., 2013), this intrinsic value of physical exertion would result in little or no effect of the previous mental exertion on the performance of these athletes.

Though, these are speculations that require empirical evidence. Future studies should compare the effect of mentally demanding task on the performance of aerobic-trained children and sedentary peers, and a neurophysiological and psychological assessment should be implemented to test these hypotheses. Research on this topic should also explore potential psychological variables that mediate or influence the effect of mental fatigue on performance to improve the understanding of this phenomenon and to better interpret the results.

For example, task self-efficacy was shown to mediate the effect of self-control on the following physical performance through a sequentially mediated pathway, that was self-control tasks induced fatigue that affected task self-efficacy and, ultimately the performance on the second task (Graham and Bray, 2015; Graham et al., 2017). So far, no studies have investigated task self-efficacy as a mediator of fatigue-performance relationship in young athletes as well as in professional athletes. Hence future investigations should include this measure to assess whether they may be more resilient to the decline in self-efficacy induced with mental fatigue.

Similarly, Voce & Moston, (Voce and Moston, 2015) and Wan & Stherntal, (Wan and Stherntal, 2008) reported that performance feedback that allowed to monitor the performance level objectively could vanish the effect of ego-depletion on the subsequent cognitive performance. Performance feedback could represent a possible avenue for future research on mental fatigue and physical performance. In particular, it may be that with the practice athletes become able to better monitor the performance with their subjective feelings even in the absence of external feedback.

In conclusion, the present findings favour the hypothesis that *resistance to mental fatigue* could be a distinctive characteristic of endurance athletes and it develops at an early age (Martin et al., 2016).

Furthermore, this study showed that children endurance performance was not affected by performing a more complex cognitive task involving reasoning, decision-making and planning compared with the Stroop task.

Despite the new insight into mental efforts in trained children, the study presented some methodological limitations that should be acknowledged when interpreting the results.

Firstly, as stated above self-reported measures did not clearly distinguish the level of mental fatigue induced by the interventions. Different scales have been employed to assess the subjective state of fatigue with contradictory findings (van Cutsem et al., 2017); however, a direct comparison of these assessments and a gold standard measure of the subjective feeling of fatigue is still lacking. A multidimensional assessment comprising different neurophysiological measures (i.e. electroencephalogram) and a secondary cognitive task may be necessary to gauge the cognitive and physiological effects of the cognitive task and elucidate the relationship between mental exertion and physical performance (van Cutsem et al. 2017). In this regard, the present investigation did not include relevant psychological variables that were shown to mediate the effect of mental fatigue on physical performance such as task-self efficacy (Graham and Bray, 2015; Graham et al., 2017).

A second element requiring further attention is the type of cognitive tasks employed to induce mental fatigue. In the current study, the Stroop task was 100% incongruent, namely colour-words and ink-colour did not match in any trial. The incongruent trials of the Stroop task require higher cognitive control than the congruent trials as they elicit the inhibition of the automatic response to the colour-word (Botvinick et al., 2001). It has been reported that the response inhibition required by the incongruent Stroop task could have a negative effect on the subsequent physical performance (Englert and Wolff, 2015; Graham and Bray 2015; Martin et al., 2016; Pageaux et al., 2014). Moreover, Brown and Bray (Brown and Bray, 2017) demonstrated that this effect could be elicited for tasks as short as 6 min and persisted up to 10 min of task duration.

However, it was shown that when the incongruent stimuli were presented at a high rate, the interference effect diminished (Lindsay and Jacoby, 1994). As a consequence, the repetition of the incongruent stimuli over one hr period could reduce the interference and strengthen the colour-naming response. This could have led to more automatic responses reducing the effort required to sustain the task and ultimately, the effectiveness of the intervention. Future studies should assess the effect of different types and the lengths of the cognitive tasks on the subsequent performances. In addition to that, the manipulation of the second effortful task could also be relevant from a theoretical perspective to entangle the research on self-control and mental fatigue and their effect on physical performance.

The experimental sessions were performed on school days from 14:00 to 18:00. Therefore, it could not be excluded that the detrimental effect of mental fatigue on physical performance had already been exacerbated by other activities limiting the effect of the cognitive tasks. However, it should be noted that children were asked to abstain from any cognitive activity for at least two hours before starting the experimental sessions and the fatigue scale of the BRUMS did not display any level of fatigue in the baseline assessment. Future studies should test the same protocol during weekends to exclude the presence of a floor effect on the physical performance. In the present study, we implemented a cross-over design where the visits were randomly allocated to the subjects based on balanced permutations, yet a Williams design would be more appropriate to control for the carryover effects.

The above limitations highlighted relevant issues for the research in the field of mental fatigue and physical performance that should be addressed by future research.

Conclusions

Several studies reported that mental fatigue has a detrimental effect on endurance performance in healthy recreational athletes (van Cutsem et al., 2017). The current study is the first investigating its effect in trained children performance and provides preliminary experimental evidence that mental effort, elicited with a Stroop task or an arithmetic test, does not limit the following exercise performance in prepubertal endurance athletes. However, it should be noted that self-reports of fatigue did not differ between conditions, limiting our ability to determine the extent to which fatigue was induced by the more mentally demanding cognitive tasks. Therefore, its finding needs to be replicated by further researches implementing a broader psychophysiological assessment of mental fatigue.

Future research should investigate whether this effect depends on the age or the involvement in endurance activities comparing the response in sedentary and active children as well as across developmental years. Health interventions in paediatric settings, physical education programs as well as young athlete’s development framework could take advantage from the investigation of the perceptual and functional consequences of prolonged periods of demanding cognitive activity and its interplay with physical fatigue during the development. The study of the interplay between cognitive functions and endurance performance in young athletes could help improve talent identification programs and young athlete’s development programs.

CHAPTER FOUR

Mental fatigue impairs time trial performance in sub-elite under 23 cyclists

Filipas L, Gallo G, Pollastri L, La Torre A. Mental fatigue impairs time trial performance in sub-elite under 23 cyclists. PloS One. 2019;14(6):e0218405.

Abstract

Purpose: This study investigates the effect of a mentally demanding response inhibitory task on time trial performance in sub-elite under 23 cyclists. **Methods:** Ten under 23 road cyclists completed two separate testing sessions during which they performed two different cognitive tasks before completing a 30-min time trial on the cycle ergometer. In the experimental condition, 30 min of a standard cognitive task (Stroop task) was used to elicit mental fatigue; in the control condition, a non-demanding activity was carried out. Subjective workload and mood were measured before and after the treatments, and motivation was recorded before the time-trial. During the time trial, power, cadence, HR, and RPE were assessed. Blood lactate concentrations and HRV (using the root mean square of successive differences between adjacent R-R intervals, RMSSD) were measured before and after the time trial. **Results:** The Stroop task was rated more mentally ($p < 0.001$) and temporally ($p < 0.001$) demanding, effortful ($p < 0.001$), and frustrating ($p = 0.001$) than the control task; fatigue ($p = 0.002$) and vigor ($p = 0.018$) after the cognitive tasks were respectively higher and lower than in the control task. Mean power output ($p = 0.007$) and cadence ($p = 0.043$) were negatively affected by the Stroop task, while HR ($p = 0.349$), RPE ($p = 0.710$), blood lactate concentration ($p = 0.850$), and RMSSD ($p = 0.355$) did not differ between the two conditions. **Conclusion:** A mentally demanding activity reduced the subsequent physical performance in sub-elite under 23 cyclists. Thus, avoiding cognitive efforts before training and races could improve performance of high-level athletes.

Introduction

Mental fatigue is defined as a psychobiological state that may arise during or after prolonged cognitive activities, and it is characterized by the feelings of tiredness, decreased commitment, and increased aversion to continue the current activity (Boksem and Tops, 2008). Acute mental fatigue has a negative effect on submaximal endurance performance (van Cutsem et al., 2017): several studies in this area showed that mental fatigue impairs whole body and muscular physical endurance performance, both in close-ended tasks (Marcora et al., 2009; Pageaux et al., 2013) and in open-ended tasks (MacMahon et al., 2014; Martin et al., 2016; Pageaux et al., 2014). The underlying mechanism that can explain why mental fatigue impairs endurance performance seems to be an increased perception of effort for external and internal loads. For further explanation on this topic, see the review of Van Cutsem et al. (van Cutsem et al., 2017). The physiological reasons for an increased RPE-load ratio are not yet fully understood. A model has recently been proposed, based on the interaction between the adenosine neuromodulator and the encephalic A1 receptors (Martin et al., 2018).

Beyond the definition of the physiological mechanisms of mental fatigue, it is important to understand whether the ability to resist mental fatigue is associated with a certain degree of trainability. In a recent study, Martin and colleagues (Martin et al., 2016) demonstrated that mental fatigue impairs endurance performance (measured as power output during a 20-min time trial) in recreational cyclists, but not in professional cyclists. The authors hypothesized that superior resistance to mental fatigue may be one of the characteristics that distinguishes successful endurance athletes, together with traditional physiological and psychological abilities. It is difficult to predict the nature of this greater fatigue, resistance and to understand if this peculiar ability could be trainable. The improved performance of elite cyclists may be a result of training as there are a host of beneficial changes that occur in the brain as a result of aerobic training (Colcombe et al., 2006; Ludyga et al., 2016; Marques-Aleixo et al., 2015;

Martin et al., 2018; Matsui et al., 2011).

Although the physiological mechanisms of mental fatigue need to be further investigated, a few studies reported that acute mental fatigue can also influence the autonomic regulation of HR. Mental fatigue induces a sympathetic hyperactivity, a decrease in parasympathetic activity and, therefore, a reduction in HRV (Mizuno et al., 2011; Tanaka et al., 2009). During the last 25 years, HRV has been widely used as a non-invasive method to estimate cardiac autonomic regulation, which may reflect the activity of the autonomic nervous system (Rajendra Acharya et al., 2006). In sports, rest or post exercise HRV is growing in importance as an objective and rational method for the quantification of training load in endurance athletes (Plews et al., 2013; Saboul et al., 2016). Despite two studies demonstrated acute changes in HRV during mentally fatiguing protocols (Mizuno et al., 2011; Tanaka et al., 2009), a recent study in young swimmers showed that post treatment and post exercise HRV values could be unchanged after a mental effort (Penna et al., 2018), highlighting potential issues in the quantification of training load in mentally fatigued athletes. Athletes experience mental fatigue conditions before training or competitions (i.e. use of smartphone, long tactical sessions), therefore understand the impact of this condition on training load could be useful to evaluate it correctly.

To date, no studies have investigated the effect of mental demanding tasks on sub-elite endurance athletes, a category that could have similarities and differences to both elite and recreational athletes. Therefore, the first aim of the present study was to further investigate the effect of a mental demanding and response inhibitory task on time trial performance in sub-elite under 23 cyclists. Based on previous findings of an association between performance level and inhibitory control in elite cyclists (Martin et al., 2016) and ultramarathon runners (Cona et al., 2015), we hypothesized that under 23 cyclists' performance would be negatively affected by the mentally demanding task. The second aim of this study was to identify possible alterations in the autonomic control of HR following a prolonged mentally demanding task.

The influence of mental fatigue on HRV could be crucial to evaluate the efficacy of HRV as a predictor of training load in mentally fatigued athletes. We hypothesized that mental fatigue would not alter HRV values, as reported in the research on young swimmer, the only study that investigated HRV and mental fatigue in a sport context (Penna et al., 2018).

Methods

Subjects

Ten under 23, male road cyclists (20.0 ± 1.2 yr, 66.1 ± 7.6 kg, 180.4 ± 5.6 cm, VO_{2max} 69.0 ± 4.4 $mL \cdot min^{-1} \cdot kg^{-1}$, peak power output 380 ± 39 W, > 4 training sessions per week, > 300 km per week, > 3 years of cycling experience) voluntarily participated in this study. Participants were members of different under 23 cycling teams affiliated to the Italian Cycling Federation. Considering each participant's VO_{2max} and training history, and in line with guidelines designed to help describe the performance level of participants in sports science research (De Pauw et al., 2013), the subjects were classified as performance level 4 (well-trained). Eligibility criteria were as follows: free from any known medical diseases, injuries, color vision deficiencies and learning disorders, free from any medication. The study design and procedures were approved by the Università degli Studi di Milano Ethics Committee and followed the ethical principles for medical research involving human subjects set by the World Medical Association Declaration of Helsinki. After ethical approval, written informed consent and medical declaration were obtained from the participants in line with the procedures set by the local Institution's Research Ethics Committee. Subjects were informed of the procedures and potential risks involved. They were also informed that they were free to withdraw from the study at any time.

Experimental design

A randomised counterbalanced cross-over design was used for the experimental component of the present study. The order of the experimental treatments (intervention; control) was randomly allocated based on balanced permutations generated by a web-based computer program (www.randomization.com).

Experimental overview

Subjects performed four testing sessions on four different occasions, in a period no longer than three weeks between the first and last visit. Visits were carried out at the university laboratory. Cognitive and physical tasks were performed in an isolated and air-conditioned room, at the constant temperature of 19 ± 1 °C and at a relative humidity of about 40–50 %. Prior to each visit, participants were instructed to sleep for at least 8 h, refrain from the consumption of alcohol and caffeine, and avoid any vigorous exercise for the 36-h preceding the testing sessions. Participants were also instructed to avoid any mentally demanding tasks the day of the testing sessions. Each participant carried out the visits individually and at the same time of day (within 1 h period, between 9:00 and 12:00). During visit 1, participants weight and height were measured. Afterwards, they familiarized with the procedures employed for the experimental sessions, i.e. the Stroop task (for the time needed to reach a minimum of 95 % of accuracy), psychological questionnaires, and the physical task, i.e. a time trial on a cycling ergometer. During visit 2, participants completed an incremental exercise test to determine their VO_{2max}. A graphical representation of visit 3 and 4 is shown in Figure 4.1.

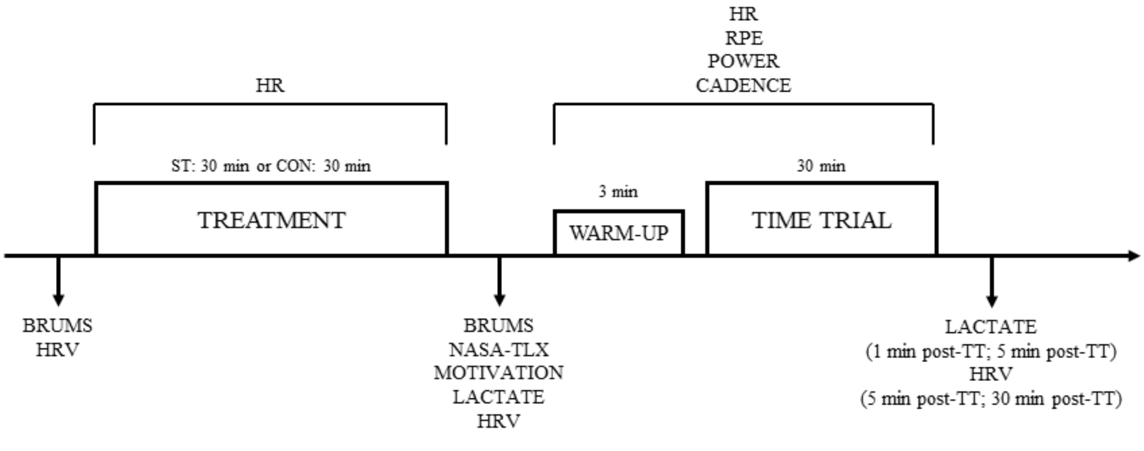

Figure 4.1. Schematic of the visits 3 and 4. HR – Heart Rate; HRV – Heart Rate Variability; RPE – Rating of Perceived Exertion; ST – Stroop Task; CON – Control.

Experimental treatment

The mental fatigue condition consisted in a 30-min modified Stroop color-word task. The Stroop task demands response inhibition and sustained attention (MacLeod and MacDonald, 2000) and has previously been shown to induce mental fatigue (van Cutsem et al., 2017). The modified Stroop task used in our protocol was the same version and had the same implementing rules described by Martin et al. (Martin et al., 2016). Participants were instructed to respond as quickly and as accurately as possible. Participants familiarized with the Stroop task for 5 min during the preliminary visit. Additionally, 24 practice attempts prior to the experimental task were allowed, to ensure the participants fully understood the instructions. The reaction time of the correct responses and accuracy were averaged for 6 blocks of 5 minutes.

The control trial involved watching a 30-min video regarding amphibious excavators under the same conditions as the Stroop task.

Physical tests

During the second visit, participants underwent an incremental exercise test on a cycle ergometer (Cyclus 2, RBM elektronik automation GmbH, Leipzig) to assess their VO_{2max}. The incremental exercise test began at 100 W and increased by 25 W every 30 s until volitional exhaustion.

Participants performed the time trial during the following two visits to the laboratory. A standardized warm-up at the constant power output of 100 W was completed by all participants prior to each time trial. Both were performed on the Cyclus 2 ergometer. Participants were instructed to cover as much distance as possible over 30 min. The time trial began in a standard gear; however, participants were free to alter gearing throughout the time trial. A timer was placed to the front right of participants and remained visible during the time trial; participants were blinded to all other performance and physiological data. After the test, mean power output and mean cadence were analyzed in 10 blocks of 3 min each. Average power and cadence during the whole-time trial were also recorded.

Physiological measures

Capillary blood samples were collected immediately before the warm-up and two times after completion of time trial (1 min and 5 min) during visits 3 and 4. Samples were analyzed immediately for blood lactate concentration using the Lactate Pro 2 (Arkray, Japan) analyzer. During visits 3 and 4, HR was recorded during the final 10 s of the 10 blocks of 3 min each using a HR monitor fitted with a chest strap.

Psychological measures

RPE was registered during the final 10 s of the 10 blocks of 3 min each with the 11-point CR10 developed by Borg (Borg, 1998). Participants were familiar with the scale as it had been employed during their daily training sessions for at least six months prior to the tests.

The BRUMS developed by Terry et al. (Terry et al., 2003) was used to assess changes in start and post-treatment mood. The questionnaire consists of 24 items divided into 6 subscales related to mood (Depression, Fatigue, Vigor, Confusion, Anger, Tension). Participants were asked to rate each item on a 5-point Likert scale (from 0 = not at all, to 4 = extremely) according to their current mood ("How do you feel right now?"). Each subscale score, with four relevant items, could range from 0 to 16.

The subjective workload was recorded after the treatments with the Italian version of the NASA-TLX (Bracco and Chiorri, 2006). It involves a multi-dimensional rating procedure with 6 subscales (Mental demand, Physical demand, Temporal demand, Effort, Frustration). Subjects were asked to rate each of them on a 0 to 20 scale anchored by bipolar descriptors (high/low). Each score was multiplied by 5 so that the final score of each subscale would range from 0 to 100.

Motivation toward time trials was measured after the treatments with a single item on a 5-point Likert scale (0 = not at all, 1 = a little bit, 2 = somewhat, 3 = very much, 4 = extremely) (Martin et al., 2016).

HRV

HRV was measured at baseline, after the Stroop task and twice after the time trial (5 min and 30 min) in both conditions. For all measurements, the participants remained in a lying position for five minutes, with a normal breathing rate, in silence and with no body movements. To collect the HR data, a Polar T61 chest belt connected to a recording watch (Polar Electro, Kempele, Finland) recorded a beat-to-beat HR at a 1-ms time resolution (Gamelin et al., 2006). Occasional ectopic beats were visually identified and manually replaced with interpolated adjacent R-R interval values. To identify the HRV in the time-domain, average R-R intervals and the RMSSD were analyzed. All analyses were performed with Kubios HRV Analysis Software v2.2 (Biosignal analysis and medical imaging group, University of Eastern Finland, Finland) (Tarvainen et al., 2014).

Statistical analysis

All data are presented as mean ± SD. Assumptions of statistical tests such as normal distribution and sphericity of data were checked as appropriate. Greenhouse-Geisser correction to the degrees of freedom was applied when violation to sphericity was present. One-way ANOVA was used to determine the effects of time for reaction time and accuracy during the Stroop task. Paired sample t tests were used to determine the effects of condition on the mean HR during the Stroop task, NASA TLX subscales, motivation related to the time trial, and average power, cadence and HR during the time trial. Repeated measures ANOVAs were used to determine the effects of condition and time for blood lactate concentration, RMSSD, mood subscales, and HR, RPE, cadence and power output during the time trial. Bonferroni tests were used if significant interactions were found. Additionally, the ES for each statistical test is reported as partial eta squared (η^2p), using the small = 0.02, medium = 0.13 and large = 0.26 interpretation for ES (Bakeman, 2005). Significance was set at 0.05 (2-tailed). All data analysis was conducted using the statistical packages for social science (SPSS version 24).

Results

Stroop task performance

There were no significant main effects of time on accuracy (overall grand mean: 95.3 ± 3.1 %, $p = 0.733$, $\eta^2p = 0.058$) and reaction time (overall grand mean: 1141 ± 206 ms, $p = 0.362$, $\eta^2p = 0.100$). There was no significant difference also in the mean HR during Stroop task and control condition (overall mean Stroop task: 49 ± 10 bpm, overall mean control: 50 ± 9 bpm, $p = 0.760$).

Psychological responses

The vigor and fatigue scale of the BRUMS revealed a significant condition x time interaction (vigor: $p = 0.018$, $\eta^2p = 0.479$, fatigue: $p = 0.002$, $\eta^2p = 0.678$). The follow-up tests revealed that the vigor scale decreased, and fatigue scale increased over time in both conditions. (vigor: $p = 0.005$, $\eta^2p = 0.605$, fatigue: $p = 0.001$, $\eta^2p = 0.744$). However, the Stroop task condition showed a greater decrease in vigor scale and increase in fatigue scale compared to the control (Figure 4.2).

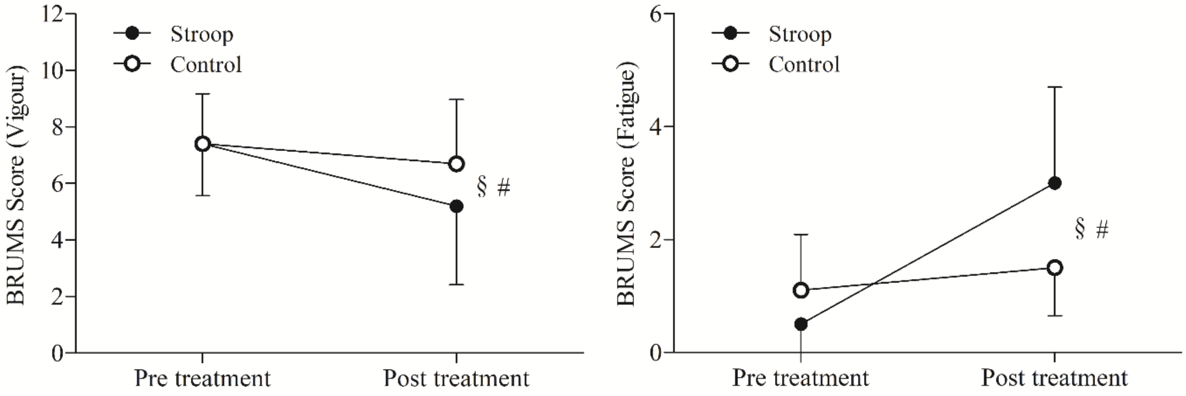

Figure 4.2. Effect of prior cognitive task on BRUMS vigor (left) and fatigue (right) index. Significant interactions condition x time (§, $p < 0.05$) and main effects of time (#, $p < 0.05$). Data are presented as mean ± SD.

NASA-TLX showed a significantly higher mental demand ($p < 0.001$), temporal demand ($p < 0.001$), effort ($p < 0.001$) and frustration ($p = 0.001$) after the Stroop task compared to the control task. Physical demand and performance did not differ between the two conditions (respectively $p = 0.560$ and $p = 1.000$). Data of subjective workload are reported in Table 4.1.

Table 4.1. NASA-TLX subjective workload values for the five subscales between the two conditions. Data are presented as mean ± SD.

	NASA-TLX workload					
	Mental demand	**Physical demand**	**Temporal demand**	**Performance**	**Effort**	**Frustration**
Stroop task	68 ± 14	13 ± 10	71 ± 17	25 ± 13	77 ± 9	46 ± 12
Control	34 ± 19	11 ± 6	35 ± 18	25 ± 13	33 ± 16	25 ± 14
p	< 0.001	0.560	< 0.001	1.000	< 0.001	< 0.001

Motivation for the time trial did not differ significantly between conditions ($p = 0.443$). Values were 3.3 ± 0.9 and 3.5 ± 0.8 for the Stroop task and the control condition respectively.

Time trial performance

There was no significant interaction condition x time ($p = 0.234$, $\eta^2p = 0.129$) for power output during the time trial. However, there was a main effect of condition (Figure 4.3), with a lower power output recorded after the Stroop task compared to control condition (overall mean Stroop task: 287 ± 23 W, overall mean control: 295 ± 23 W, $p = 0.007$, $\eta^2p = 0.574$). There was no significant main effect of time (p = 0.120, η²p = 0.207).

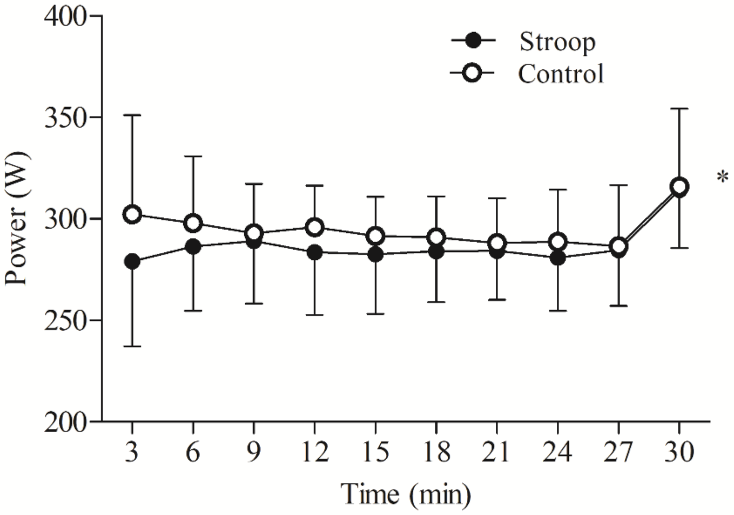

Figure 4.3. Effect of prior cognitive task on power output during the 30-min time trial. Significant main effect of condition (, p < 0.05). Data are presented as mean ± SD.*

There was no significant interaction condition x time (p = 0.508, η²p = 0.081) for cadence during the time trial. However, there was a main effect of condition (Figure 4.4), with a significant lower cadence after the Stroop task compared to the control condition (overall mean Stroop task: 100 ± 7 rpm, overall mean control: 102 ± 6 rpm, p = 0.043, η²p = 0.382). There was no significant main effect of time (p = 0.373, η²p = 0.106).

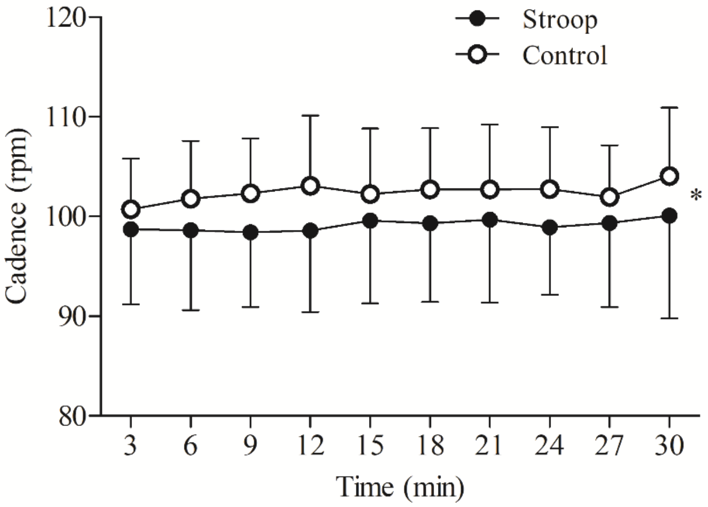

Figure 4.4. Effect of prior cognitive task on cadence during the 30-min time trial. Significant

main effect of condition (, $p < 0.05$). Data are presented as mean ± SD.*

Physiological and perceptual responses during the time trial

There was no significant interaction condition x time ($p = 0.919$, $\eta^2p = 0.002$) for blood lactate concentrations. There was no main effect of condition ($p = 0.850$, $\eta^2p = 0.004$), but lactate was higher after time trial compared to baseline ($p < 0.001$, $\eta^2p = 0.848$). Mean blood lactate concentrations for the Stroop task and the control condition were respectively 1.3 ± 0.2 $mmol.l^{-1}$ and 1.3 ± 0.2 $mmol.l^{-1}$ at the baseline, 7.7 ± 3.5 $mmol.l^{-1}$ and 7.8 ± 2.6 $mmol.l^{-1}$ one minute after the time trial, 6.7 ± 2.5 $mmol.l^{-1}$ and 6.9 ± 2.6 $mmol.l^{-1}$ five minutes after the time trial.

There was no significant condition x time interaction ($p = 0.616$, $\eta^2p = 0.054$) for HR during the time trial. There was no main effect of condition ($p = 0.349$, $\eta^2p = 0.098$). However, HR increased over time in both conditions (overall mean Stroop task: 172 ± 6 bpm, overall mean control: 173 ± 7 bpm, $p < 0.001$, $\eta^2p = 0.847$).

There was no significant condition x time interaction ($p = 0.694$, $\eta^2p = 0.054$) for RPE during the time trial (Figure 4.5). There was no significant main effect of condition ($p = 0.710$, $\eta^2p = 0.016$). However, RPE increased over time in both conditions ($p < 0.001$, $\eta^2p = 0.851$).

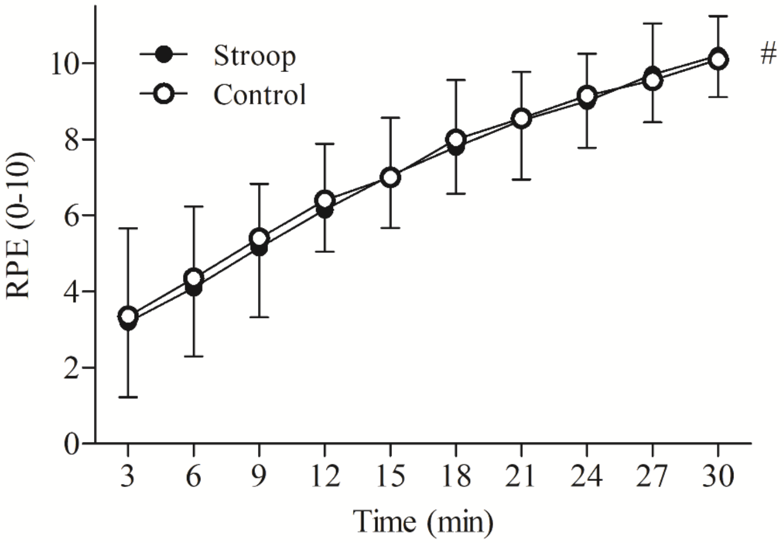

Figure 4.5. Effect of prior cognitive task on rating of perceived exertion (RPE) during the 30-

min time trial. Significant main effect of time (#, $p < 0.05$). Data are presented as mean ± SD.

HRV responses

There was no significant condition x time interaction ($p = 0.711$, $\eta^2p = 0.049$) for RMSSD values. No main effect of condition was found ($p = 0.392$, $\eta^2p = 0.082$), but only a main effect of time ($p < 0.001$, $\eta^2p = 0.890$). Specifically, HRV decreased more 5 min after the time trial, compared to 30 min. Mean RMSSD values for the Stroop task and the control condition were respectively 62.2 ± 14.2 ms and 63.1 ± 14.7 ms at baseline, 60.4 ± 17.7 ms and 62.8 ± 17.4 ms after the Stroop tasks, 6.5 ± 4.4 ms and 6.0 ± 2.5 ms five minutes after the time trial, 20.8 ± 17.0 ms and 22.4 ± 19.4 ms thirty minutes after the time trial.

Discussion

The first aim of this study was to investigate the effect of a mentally demanding response inhibitory task on time trial performance in sub-elite under 23 cyclists. In accordance with our hypotheses, results suggest that the mentally demanding task impaired endurance performance via a reduction in average power output and cadence during the 30-min cycling time trial, without a change in physiological and perceptual responses. The second aim of this research was to identify possible alterations in the autonomic control of HR following a prolonged mental demanding task. As hypothesized, mental fatigue did not alter HRV values, both after the Stroop tasks and the time trial.

The two psychological questionnaires (BRUMS and NASA-TLX) highlighted that mental fatigue was induced by the Stroop task, even if accuracy and reaction time did not change significantly during the response inhibition task. A similar result was previously found in other research on the same topic (Filipas et al., 2018; Pageaux et al., 2013). The authors employed two different intervention tasks to induce mental fatigue. None of these affected accuracy and reaction time during the task. However, BRUMS (Pageaux et al., 2013) and NASA-TLX (Filipas et al., 2018) showed an increased mental fatigue after the task compared to the control condition. The findings of these studies suggest that the subjects probably drained themselves trying to keep the same reaction time and accuracy during the Stroop tasks. Comparing the Stroop task performances with the study by Martin et al. (Martin et al., 2016), we found that reaction time in the under 23 cyclists tended to be constant throughout the task, as it did in the elite cyclists. Globally, the higher reaction time of our subjects could explain the lack of reduction in Stroop task performance (greater focus on overall accuracy). Therefore, the use of questionnaires, associated with the analysis of reaction time and accuracy, could probably help to check the effectiveness of the Stroop task to induce mental fatigue.

The response inhibition task significantly impaired performance during the 30-min time trial, in terms of power output and cadence. Although the time trails are slightly different in terms of duration (20 min vs 30 min), we found some similarities with recreational cyclists in Martin et al. (Martin et al., 2016): sub-elite under 23 cyclists were negatively affected by a mentally demanding task. This confirms that this group of cyclists has some similarities to recreational cyclists, but also to professional ones. Indeed, the decrease of performance between control and mental fatigue condition in under 23 athletes is relatively small (~ 2.8 %), but almost exactly in the middle between the ~ 0.9 % reduction of elite cyclists and the ~ 5.8 % reduction for the recreational cyclists. Acknowledging the limitation of this descriptive comparison, we could assume a progressive greater tolerance to mental fatigue from low to high level endurance athletes.

As found in previous studies (Pageaux and Lepers, 2016), both HR and blood lactate concentrations remained similar in the mental fatigue and control conditions. Indeed, according to the literature on this topic (van Cutsem et al., 2017), mental fatigue seems to be able to alter endurance performance without altering any exercise-induced physiological parameter.

Interestingly, but not surprisingly, RPE was also unaffected by mental fatigue. The current general opinion is that endurance performance is impaired by mental fatigue and this is predominantly mediated by the higher than normal perceived exertion during exercise (van Cutsem et al., 2017). This is the situation of a time to task failure test, where power output remains constant through the test. In a time-trial test, power output fluctuates during the test and the pacing strategy could affect the perception of effort (Thomas et al., 2013; Tucker and Noakes, 2009). In the present study, the subjects perceived a similar effort at each time point in the two conditions, but power output was higher in the control condition than in the mental fatigue condition. Therefore, mental fatigue induced a higher RPE/power output ratio. This finding confirms that perceived exertion plays a key role in the reduction in endurance performance after a mental fatiguing task. The underlying mechanisms behind the increased perceived exertion induced by fatigue remain unclear, but recent studies (Martin et al., 2018; Pageaux et al., 2016) speculate that an increase in extracellular concentrations of adenosine caused by prior physical exertion could explain the increased perceived exertion caused by mental fatigue.

The lower cadence found after mental fatigue was unexpected because no other study found a similar result. Therefore, we can only speculate that a possible explanation could lie in the same mechanism of template RPE discussed above. Different studies reported that higher RPE is traditionally associated with higher cycling cadence (Agrícola et al., 2017; Marsh and Martin, 1998). Hence, the higher relative perception of fatigue after the Stroop task could have induced a reduction of cadence (accompanied by a reduction in power output) to restore an appropriate RPE trajectory.

The mental fatigue protocol did not change HRV in the present study. As such, changes in HRV cannot be attributed to any acute physical impairment caused by mental fatigue. This result confirms what was found by Penna and colleagues (Penna et al., 2018) in young swimmers, but contrasts with other two previous studies (Mizuno et al., 2011; Tanaka et al., 2009) that showed a reduced HRV during a mental fatiguing task. Probably, some changes would have been found if we had measured HRV during the Stroop task. But, our goal was to check if HRV could be a good method to predict training load in a mentally fatigued condition. Ultimately, HRV seems an unsensitive marker of mental fatigue in well-trained athletes.

Practical applications

The findings of this study are important for coaches and professionals who are responsible for the planning and execution of training programs. Athletes should avoid cognitive efforts before training and races to prevent negative effects on their endurance performances. This is even more important for this this specific age group, because they suffer from mental fatigue daily at school or at work and could experience this condition more often than professional athletes. Moreover, the results of the present study highlight that HRV cannot be considered a useful measure to evaluate the additional load caused by mental fatigue.

Conclusions

Previous studies showed that mental fatigue impairs physical performance in different endurance sports, especially in recreational and amateur athletes. This investigation highlights that a mentally demanding activity reduced the subsequent physical performance in sub-elite under 23 cyclists.

CHAPTER FIVE

Effects of mental fatigue on soccer-specific performance in young players

Filipas L, Borghi S, La Torre A, Smith MR. Effects of mental fatigue on soccer-specific performance in young players. Medicine & Science in Sports & Exercise. (Under review).

Abstract

Purpose: To investigate the effects of mental fatigue on soccer-specific physical and technical performance in young players. **Methods:** Twelve U14, twelve U16 and twelve U18 soccer players completed the two parts of the investigation. Part one assessed the soccer-specific physical performance using the Yo-Yo IR1. Part two assessed the soccer-specific technical performance using the LSPT and LSST. Each part was preceded by 30 min of Stroop task (mentally fatiguing task) or 15 min of reading magazines (control task) performed in a randomised and counterbalanced order. Subjective ratings of mental fatigue and motivation were measured before and after the tasks. Distance, HR, and RPE were recorded during the Yo-Yo IR1. LSPT and LSST scores were calculated. **Results:** Subjective ratings of mental fatigue were higher after the Stroop task compared to the control in U14, U16 and U18 in both parts. Mental fatigue significantly reduced Yo-Yo IR1 distance in the three age groups, alongside an increase in HR and RPE. For LSPT, original time, penalty time and performance time were significantly higher in the mental fatigue condition than in the control condition in U18. For LSST, points per shot, shot speed and shot sequence time were not significantly different between conditions in U14, U16 or U18. **Conclusion:** Mental fatigue reduced soccer-specific physical performance in U14, U16 and U18 players, without alteration of technical performance, except for LSPT in U18.

Introduction

Acute mental fatigue is defined as a psychobiological state that may arise during or after prolonged cognitive activities; it is characterized by feelings of tiredness or even exhaustion, and a decreased commitment and increased aversion to continue the current activity (Boksem and Tops, 2008). Acute mental fatigue has an adverse effect on cognitive function (Lorist et al., 2005; van der Linden et al., 2003) and endurance exercise performance (van Cutsem et al., 2017). Recent research has also revealed the negative impact of mental fatigue on soccer performance (Smith et al., 2018).

Soccer (like most intermittent team sports) is a complex sport, with multiple factors contributing to successful performance (Coutinho et al., 2018). Recent research has revealed that mental fatigue impairs many of these factors, including physical (Smith et al., 2016; van Cutsem et al., 2017), technical (Smith et al., 2016), decision-making (Slimani et al., 2016), and tactical (Smith et al., 2018). Based on these results, it has been suggested that soccer players should avoid mentally fatiguing tasks prior to competition and/or implement strategies to reduce the impact of mental fatigue (Slimani et al., 2016). However, participants in these previous investigations were adults, and therefore future research may be required in younger athletes.

Throughout school days young athletes are engaged in mentally demanding activities such as classes, exams and homework that they alternate with training sessions and/or competitions. Therefore, it would be relevant for these athletes establishing the impact of activities that require mental effort on their physical performance. Furthermore, performance at school and adjusting training due to school commitments have been cited as potential factors leading to burnout among junior tennis players (Gould et al., 1996) and golfers (Cohn, 1990). Hence, studying the relationship between acute mental fatigue and physical performance in young athletes could promote adequate strategies for reducing mental fatigue in young athletes.

In a recent study, we observed a tolerance to mental fatigue in young (aged 10 - 11 y) rowers

(Filipas et al., 2018), which contrasts results from studies of adult endurance athletes (van Cutsem et al., 2017). However, no previous research has examined whether age influences the previously observed negative effects of mental fatigue on soccer-specific performance.

Therefore, the purpose of the present study was to investigate the effects of mental fatigue on physical and technical performance in different age groups of young soccer players assessed using the Yo-Yo IR1 and the LSPT and LSST. Based on recent evidence that young athletes may be less effected by mental fatigue (Filipas et al., 2018), we hypothesised that age would mediate the effects of mental fatigue on physical and technical performance in young soccer players.

Methods

Participants

Thirty-six young male soccer players; twelve U14 (height: 168 ± 4 cm, weight: 55 ± 8 kg), twelve U16 (height: 170 ± 5 cm, weight: 62 ± 8 kg) and twelve U18 (height: 177 ± 7 cm, weight: 69 ± 8 kg), voluntarily participated in this study. All participants were recruited from a local soccer team competing at national level (> 3 years of soccer experience). The inclusion criteria included being aged between 13 and 18 years, practicing soccer for at least three years, not playing as a goalkeeper, and successfully completing the pre-exercise screening. The exclusion criteria included having any medical condition or injury that prohibited the participants from being able to complete the physical and technical components of the study, having a diagnosed sleep disorder or known colour-vision impairments. All participants provided written informed consent before participation. Parental consent was provided for participants younger than 18 y, and procedures set by the university ethics committee for dealing with minors were followed. All procedures were approved by the local research ethics committees and follow the ethical principles for medical research involving human subjects set by the World Medical Association

Declaration of Helsinki. Participants were provided with written instructions outlining the studies procedures but were not informed of their aims. Participants were told that the study sought to compare the mental and physical preparedness of young soccer players.

Experimental overview

The protocol was divided in two parts (physical and technical tests) and both were randomised, counterbalanced crossover trials. Participants visited the respective testing facilities on three separate occasions for each part, with the first visit of each part functioning as a familiarisation session. The remaining two visits (control and mental fatigue sessions) were performed in a randomized and counterbalanced order generated by online software (ww.randomization.com). The researchers assessing the outcome measures were blinded to treatment. All the testing sessions were performed at a temperature of 22 ± 3 °C. Prior to each visit, participants were instructed to sleep for at least 7 h, refrain from the consumption of alcohol and caffeine, and avoid any vigorous exercise the day before the testing. Participants were also instructed to avoid any mentally demanding tasks the day of the testing sessions. Compliance with these instructions was assessed with pre-test checklists upon arrival for the testing sessions. Each participant carried out the visits individually, at the same time of day (within 1 h period, between 9:00 and 12:00 for the testing sessions) and separated by 1 week (both the physical and technical parts).

Experimental procedures

The procedures were the same as those used by Smith and colleagues (Smith et al., 2016) in a previous study. This approach was used to be able to compare the result of these two studies. Therefore, for the purpose of this manuscript all the procedures have been briefly reported.

During the weeks before the start of the protocol, participants were provided with standardized instructions for memory anchoring of Borg’s 6 to 20 RPE scale (Borg, 1970) as well as visual analogue scales (VAS) for the assessment of mental fatigue and motivation, and the NASA-

TLX for assessing subjective workload.

Part one

During the first session, participants were familiarised with the mentally fatiguing task (Stroop task) and the Yo-Yo IR1. During the following two visits, in the control session, participants leisurely read for 15 min from a selection of emotionally neutral online magazines; in the mental fatigue session, participants completed for 30 min a computerised and modified version of the incongruent Stroop colour-word task. Interventions were not time-matched as pilot testing revealed excessive boredom following 30-min of reading online magazines. The subjective level of mental fatigue and motivation were then assessed with VAS, along with the subjective workload using NASA-TLX. Participants performed a 3-min standardised running warm-up and the Yo-Yo IR1. The Yo-Yo IR1 is a valid and reliable test of physical performance for soccer players (Bangsbo et al., 2008). The test involves repeating 2 x 20 m runs (up and back = 1 sprint) between cones at progressively increasing velocities. Runs are separated by 10 s of active recovery in which the soccer player walks or jogs around a cone 5 m away and returns to the starting line. Participants continue the test until they fail to reach the finish line in time on two occasions. The Yo-Yo IR1 was completed on a synthetic outdoor field. HR (Polar M400, Polar Electro 2016, Oy, Kempele, Finland) and RPE were recorded at the end of each level of the Yo-Yo IR1 (plus at exhaustion). Total distance covered was recorded at the end of the test. In both conditions, participants were instructed to run until exhaustion without any motivational intervention provided by the researchers.

Part two

During the first visit, participants were familiarised with the LSPT and LSST. Participants performed five trials of the LSPT and twelve shot sequences of the LSST. The final two visits followed the same procedures as those of part one, until the warm-up. Participants completed a 3-min warm-up with a ball, incorporating passing, dribbling, and ball control elements. After warm-up, participants completed two trials of the LSPT; separated by a 1-min rest. After another 2-min rest, participants completed two trials of the LSST, separated by a 3-min rest. This 3-min rest comprised 2 min of passive rest, followed by 1 min of active rest with the ball. Results from both trials in the LSPT and LSST were averaged. Therefore, all procedures were completed within 30 min of finishing the cognitive tasks. The LSPT and LSST were developed and validated by Ali and colleagues (Ali et al., 2007) to assess soccer-specific technical performance. In the LSPT, participants were required to make 16 passes (of 4 or 3.5 m) against standard gymnasium benches, positioned in a rectangle around the player. A coloured piece of cardboard (0.6 x 0.3 m) was attached to each bench, serving as a target area, and passes were performed in one of four randomised colour orders selected by a blinded investigator. Participants were instructed to complete the 16 passes as fast as possible, while minimizing errors. The measures for the LSPT included original time (time to complete all 16 passes), penalty time (additional time for errors, inaccurate passes, and slow performance), and performance time (original time + penalty time). Penalty time was calculated according to the following criteria: + 5 s for completely missing the bench or passing to the wrong bench; + 3 s for missing the target area; + 3 s for handling the ball; + 2 s for passing the ball from outside of the passing area; + 2 s if the ball touched any cone; + 1 s for every second taken over the allocated 43 s to complete the test; - 1 s for each pass that hit the 10-cm strip in the middle of the target.

In the LSST participants began the test 20 m away from the goal line, with their back to the goal. They were required to sprint and touch one of two cones (left or right) positioned 6 m diagonally behind them. Participants then returned to the starting position and passed a ball against a bench before turning and shooting the ball at goal. After that, participants sprinted past the stationary goalkeeper. Each trial was made up of 10 shots (5 with each foot). Performance in the LSST was assessed using shot accuracy, shot speed, and shot sequence time.

Shot accuracy was calculated as the mean of the total points accumulated from all shots on target. Score zones were arranged to encourage shooting toward the corners of the goal, and points were only scored if the ball struck the open space of the goal (opposite side to the goalkeeper). Time to complete each shot sequence and shot speed were estimated using high-speed (240 frames per second) video recording and video analysis software (Kinovea Open Source Project, www.kinovea.org). Given the lower technical and physical ability of young football players, we did not discount those shots that took more than 8.5 s to complete and/or were struck less than 64 $km \cdot h^{-1}$, as suggested by Ali and colleagues (Ali et al., 2007).

Mental fatigue and control tasks

The mental exertion condition consisted of a 30-min computerised and modified incongruent Stroop colour-word task. The Stroop task demands response inhibition and sustained attention (MacLeod and MacDonald, 2000) and has previously been shown to induce mental fatigue (van Cutsem et al., 2017). The modified Stroop task used in our protocol was the same version and had the same implementing rules described in Martin and colleagues' study (Martin et al., 2016). Participants were instructed to respond as quickly and accurately as possible. Participants were familiarised with the Stroop task during the preliminary visit, in addition prior to the experimental task, 3 min of practice attempts were allowed to ensure the participants fully understood the instruction. The reaction time of the correct responses and accuracy were averaged for 2 blocks of 15 min.

The control condition involved 15 min of reading at a leisurely pace from a selection of online sport magazines. Participants completed both treatments in the same room, under the supervision of the same researcher.

Subjective perceptions

Participants subjective assessments of mood and perceived workload were recorded using VAS and NASA-TLX, respectively. VAS were used to assess perceptions of mental fatigue and motivation toward the upcoming physical test. Participants marked their response on a 100-mm line anchored by 0 (no mental fatigue at all) and 100 (maximal mental fatigue), and 0 (no motivation at all) and 100 (maximal motivation) for the mental fatigue and motivation scales respectively. Participant responses were measured from the left anchor and expressed in mm. The NASA-TLX was used to assess mental demand, physical demand, temporal demand, effort, performance and frustration. The scales were divided into 20 equal intervals by vertical tick marks and anchored at one end with 'very low' and the other with 'very high'. Recorded data were multiplied by 5 to provide a rating out of 100. The two questionnaires were completed by participants before and after the mentally fatiguing and control tasks.

Statistical analysis

Data are presented as mean ± SD. Firstly, statistical analyses were performed separately for the three age groups. After testing for normality, distance covered in the Yo-Yo IR1, HR and RPE (at exhaustion), LSPT scores, LSST scores, VAS mental fatigue, VAS motivation and NASA-TLX index were analyzed using paired samples t tests. HR, RPE (during Yo-Yo IR1), accuracy and reaction time during the Stroop task were analyzed using two-way (condition x time) fully repeated-measures ANOVA. Analysis of variance for HR and RPE (during Yo-Yo IR1) data included values measured at the end of each level of the Yo-Yo IR1, up to 760 m (end of level 14). Values recorded beyond this point were excluded from analysis as players began to drop out of the test from level 14 onward. If significant differences were found, between-age differences were analysed using repeated-measures two-way (age x condition) or three-way (age x condition x time) ANOVA. The Greenhouse–Geisser correction was used when the sphericity assumption was violated. Significance was set at 0.05 (two-tailed). Statistical analysis was completed using SPSS (IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp). Cohen's d ES was calculated for all significant differences using the pooled SD as the denominator and the difference between group means as the numerator (Cohen, 1988). The ES was classified as trivial (< 0.2), small (> 0.2-0.6), moderate (> 0.6-1.2) or large (> 1.2) (Batterham and Hopkins, 2006).

Results

Part one

Manipulation check

Accuracy and reaction time of the Stroop task did not change over time in the three different groups. Subjective ratings of mental fatigue were higher after the Stroop task compared to the control in U14 (Stroop: 63 ± 16 vs Control: 25 ± 19; p < 0.001; ES = 1.47), U16 (Stroop: 70 ± 13 vs Control: 30 ± 13; p < 0.001; ES = 1.66) and U18 (Stroop: 79 ± 13 vs Control: 27 ± 16; p < 0.001; ES = 1.73). There was no significant age x condition interaction for subjective ratings of mental fatigue. Motivation for the upcoming Yo-Yo IR1 remained similar in Stroop task and control conditions in U14 (Stroop: 54 ± 25 vs Control: 57 ± 24), U16 (Stroop: 68 ± 13 vs Control: 61 ± 10) and U18 (Stroop: 56 ± 20 vs Control: 60 ± 12). The subjective workload assessed using NASA-TLX showed that Stroop task was rated more mentally demanding, temporally demanding, effortful and frustrating than control condition in U14 (Mental demand - Stroop: 73 ± 13 vs Control: 8 ± 3; p < 0.001; ES = 1.89; Temporal demand - Stroop: 52 ± 19 vs Control: 10 ± 6; p < 0.001; ES = 1.64; Effort - Stroop: 65 ± 20 vs Control: 8 ± 2; p < 0.001; ES = 1.77; Frustration - Stroop: 43 ± 23 vs Control: 10 ± 3; p < 0.001; ES = 1.42), U16 (Mental demand - Stroop: 66 ± 11 vs Control: 9 ± 4; p < 0.001; ES = 1.89; Temporal demand - Stroop: 52 ± 22 vs Control: 10 ± 5; p < 0.001; ES = 1.57; Effort - Stroop: 67 ± 12 vs Control: 9 ± 5; p < 0.001; ES = 1.87; Frustration - Stroop: 37 ± 25 vs Control: 10 ± 5; p = 0.002; ES = 1.19) and U18 (Mental demand - Stroop: 59 ± 18 vs Control: 10 ± 3; p < 0.001; ES = 1.75; Temporal demand - Stroop: 62 ± 17 vs Control: 8 ± 3; p < 0.001; ES = 1.79; Effort - Stroop: 69 ± 18 vs Control: 8 ± 6; p < 0.001; ES = 1.81; Frustration - Stroop: 58 ± 17 vs Control: 12 ± 4; p < 0.001;

ES = 1.75). There was no significant age x condition interaction for NASA-TLX.

Physical tests

Figure 5.1 displays the individual distances covered during the Yo-Yo IR1. On average, participants covered significantly shorter distances in the mental fatigue condition than in the control condition in U14 (Stroop: 1057 ± 238 m vs Control: 1203 ± 277 m; $p = 0.008$; ES = 0.56), U16 (Stroop: 1090 ± 357 m vs Control: 1287 ± 302 m; $p = 0.014$; ES = 0.58) and U18 (Stroop: 1143 ± 196 m vs Control: 1400 ± 181 m; $p < 0.001$; ES = 1.13). There was a significant age x condition interaction for distances covered during the Yo-Yo IR1 ($p = 0.018$). No significant effects of session order existed for Yo-Yo IR1 performance in the three groups.

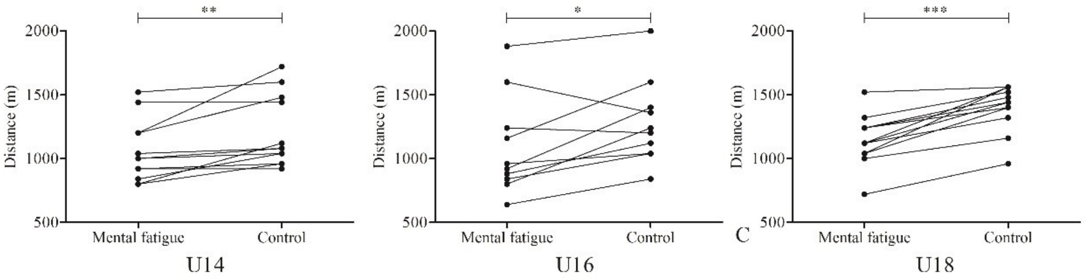

Figure 5.1. Individual distances covered during the Yo-Yo IR1 in U14, U16 and U18. Significant difference between the conditions (, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$).*

Table 5.1 shows HR and RPE for the three groups during the Yo-Yo IR1. No significant condition x time interactions were observed for HR or RPE. During the Yo-Yo IR1, HR and RPE at iso-time were significantly higher in the mental fatigue condition than in the control condition in U14 (HR - main effect of condition: F (5, 128) = 20.43; $p < 0.001$; RPE - main effect of condition: F (5, 128) = 29.72; $p < 0.001$), U16 (HR - main effect of condition: F (5, 128) = 6.29; $p = 0.007$; RPE - main effect of condition: F (5, 128) = 39.90; $p < 0.001$) and U18 (HR - main effect of condition: F (5, 128) = 5.71; $p = 0.023$; RPE - main effect of condition: F (5, 128) = 51.35; $p < 0.001$). No significant differences in HR or RPE were measured at the point of exhaustion. There was no significant age x condition x time interaction for HR or RPE.

*Table 5.1. HR and RPE at the different time-points of the Yo-Yo IR1 in U14, U16 and U18. *Significantly higher than CON (p < 0.05). Values presented as mean ± SD.*

			Start	40 m	80 m	160 m	280 m	440 m	760 m	End
U14	HR	MF	65 ± 8	136 ± 10*	150 ± 8	166 ± 7*	176 ± 6	181 ± 6	188 ± 5	194 ± 5
		CON	63 ± 7	133 ± 11	147 ± 7	161 ± 8	174 ± 6	179 ± 6	186 ± 5	196 ± 3
	RPE	MF		10 ± 2	11 ± 2	14 ± 2*	15 ± 2	17 ± 2	18 ± 1*	19 ± 1
		CON		9 ± 2	10 ± 2	12 ± 2	14 ± 2	16 ± 1	17 ± 1	19 ± 1
U16	HR	MF	60 ± 5	132 ± 9*	144 ± 8*	162 ± 5	174 ± 6*	181 ± 7	193 ± 8*	196 ± 6
		CON	59 ± 6	124 ± 13	139 ± 13	159 ± 8	169 ± 6	178 ± 6	189 ± 6	195 ± 6
	RPE	MF		8 ± 2	10 ± 2*	12 ± 3	14 ± 2*	15 ± 2	17 ± 1*	19 ± 2
		CON		7 ± 3	8 ± 2	10 ± 2	12 ± 3	14 ± 2	16 ± 1	19 ± 1
U18	HR	MF	58 ± 7	120 ± 9	135 ± 8	154 ± 9*	166 ± 8*	173 ± 7	181 ± 7	190 ± 3
		CON	58 ± 6	116 ± 11	132 ± 13	150 ± 9	161 ± 9	169 ± 9	178 ± 5	188 ± 4
	RPE	MF		7 ± 2	10 ± 3	13 ± 2*	15 ± 2*	16 ± 2*	17 ± 2	19 ± 1
		CON		7 ± 2	9 ± 2	11 ± 2	12 ± 2	14 ± 2	15 ± 2	19 ± 2

Part two

Manipulation check

Accuracy and reaction time of the Stroop task did not change over time in the three different groups. Subjective ratings of mental fatigue were higher after the Stroop task compared to the control in U14 (Stroop: 62 ± 20 vs Control: 40 ± 26; $p < 0.001$; ES = 0.85), U16 (Stroop: 65 ± 17 vs Control: 40 ± 17; $p < 0.001$; ES = 1.21) and U18 (Stroop: 69 ± 11 vs Control: 33 ± 17; $p < 0.001$; ES = 1.56). There was no significant age x condition interaction for subjective ratings of mental fatigue. Motivation for the upcoming LSPT and LSST remained similar in Stroop task and control conditions in U14 (Stroop: 53 ± 22 vs Control: 57 ± 21), U16 (Stroop: 72 ± 12 vs Control: 70 ± 13) and U18 (Stroop: 70 ± 21 vs Control: 73 ± 14). The subjective workload assessed using NASA-TLX showed that Stroop task was rated more mentally demanding, temporally demanding, effortful and frustrating than control condition in U14 (Mental demand - Stroop: 73 ± 16 vs Control: 9 ± 4; $p < 0.001$; ES = 1.85; Temporal demand - Stroop: 58 ± 19 vs Control: 9 ± 3; $p < 0.001$; ES = 1.72; Effort - Stroop: 65 ± 21 vs Control: 8 ± 4; $p < 0.001$; ES = 1.74; Frustration - Stroop: 43 ± 22 vs Control: 8 ± 3; $p < 0.001$; ES = 1.50), U16 (Mental demand - Stroop: 66 ± 14 vs Control: 9 ± 2; $p < 0.001$; ES = 1.85; Temporal demand - Stroop: 60 ± 30 vs Control: 12 ± 4; $p < 0.001$; ES = 1.50; Effort - Stroop: 65 ± 20 vs Control: 10 ± 3; $p < 0.001$; ES = 1.75; Frustration - Stroop: 44 ± 17 vs Control: 8 ± 3; $p < 0.001$; ES = 1.65) and U18 (Mental demand - Stroop: 56 ± 16 vs Control: 8 ± 3; $p < 0.001$; ES = 1.78; Temporal demand - Stroop: 61 ± 19 vs Control: 10 ± 3; $p < 0.001$; ES = 1.75; Effort - Stroop: 63 ± 17 vs Control: 8 ± 3; $p < 0.001$; ES = 1.80; Frustration - Stroop: 48 ± 22 vs Control: 12 ± 4; $p < 0.001$; ES = 1.51). There was no significant age x condition interaction for NASA-TLX.

Technical tests

A summary of the LSPT scores for both conditions in U14, U16 and U18 is presented in Table 5.2. Original time, penalty time and performance time were significantly higher in the mental fatigue condition than in the control condition in U18. No differences were found in U14 and U16. There was no significant age x condition interaction for LSPT. No significant effects of session order existed for original time, penalty time, or performance time.

Table 5.2. Effects of mental fatigue on LSPT performance. Values presented as mean ± SD.

		Original time (s)	Penalty time (s)	Performance time (s)
U14	Mental fatigue	47.6 ± 3.9	19.9 ± 8.5	67.5 ± 11.0
	Control	46.5 ± 3.1	16.4 ± 7.8	62.8 ± 10.4

	p	0.177	0.107	0.075
	ES	0.32	0.42	0.43
U16	Mental fatigue	46.7 ± 4.8	15.0 ± 7.7	61.7 ± 11.3
	Control	46.7 ± 4.4	12.5 ± 6.7	59.2 ± 9.8
	p	0.962	0.135	0.260
	ES	0.01	0.35	0.24
U18	Mental fatigue	51.9 ± 5.0	15.3 ± 4.7	67.2 ± 7.4
	Control	49.1 ± 3.9	8.0 ± 3.1	57.2 ± 6.7
	p	0.013	< 0.001	< 0.001
	ES	0.60	1.35	1.17

A summary of the LSST scores for both conditions in U14, U16 and U18 is presented in Table 5.3. Points per shot, shot speed and shot sequence time were not significantly different between conditions in U14, U16 and U18. There was no significant age x condition interaction for LSST. No significant effects of session order existed for shot accuracy, shot speed, or shot sequence time.

Table 5.3. Effects of mental fatigue on LSST performance. Values presented as mean ± SD.

		Points per shot	Shot speed (km.h^{-1})	Shot sequence time (s)
U14	Mental fatigue	1.1 ± 0.4	52.3 ± 5.0	9.5 ± 0.5
	Control	1.3 ± 0.5	55.4 ± 4.7	9.7 ± 0.6
	p	0.159	0.053	0.103
	ES	0.52	0.63	0.49
U16	Mental fatigue	1.0 ± 0.2	55.6 ± 7.1	8.6 ± 0.5
	Control	1.1 ± 0.5	56.8 ± 7.5	8.5 ± 0.4

	p	0.661	0.342	0.420
	ES	0.19	0.16	0.21
U18	Mental fatigue	1.0 ± 0.3	61.4 ± 7.7	9.7 ± 1.0
	Control	1.0 ± 0.5	64.0 ± 5.1	9.4 ± 0.7
	p	0.907	0.148	0.115
	ES	0.04	0.41	0.41

Discussion

The current investigation used two separate protocols to test the hypothesis that mental fatigue impairs soccer-specific physical and technical performance in different age groups of young soccer players. Mental fatigue reduced distances covered during the Yo-Yo IR1 for all age groups, which was in discordance with our hypothesis that age would mediate performance decrements. On the contrary, technical performance was not negatively affected by mental fatigue, except for LSPT in U18.

Mental fatigue was induced in both parts using a modified incongruent Stroop colour-word task. It has been reported that the response inhibition required by the incongruent Stroop task could have a negative effect on the reaction time and accuracy over the task (van Cutsem et al., 2017). Although in the present study reaction time and accuracy did not change over the 30-min task, this fact is unsurprising because in our previous research on young rowers (Filipas et al., 2018) accuracy and reaction time were not affected by the Stroop task. The current results align with these previous findings, with a higher subjective rating of mental fatigue after the Stroop task. In a recent study, VAS has been evaluated as the most practical method for assessing mental fatigue (Smith et al., 2019).

In the present study, intermittent running performance was negatively affected by mental fatigue in the three age groups. A similar result was found in the same test in adult soccer players (Smith et al., 2016), and in an intermittent running test simulating the demands of team sport competitions (Smith et al., 2015). Our results confirm that mental fatigue impairs soccer specific physical performance also in young soccer players, partly independently from their age group. In the present study, the performance reduction in the Yo-Yo IR1 was significant in U14, U16 and U18, with an average impairment of 12 %, 15 % and 18 % respectively, showing that younger players are less negatively affected by mental fatigue than older ones. A plausible explanation could be found comparing this study with the only two that investigated young athletes (Filipas et al., 2018; Penna et al., 2018), where younger rowers (~ 11 years) were not impaired by a mental exertion task while older young swimmers (~ 15 years) reduced significantly their 1500-m performance. The greater reduction in performance of older players in our study could be explained by the differences in the cognitive processes between adults and children. Behavioral and neuroimaging studies have reported that brain areas underlying response inhibition develop between 12 and 17 years and peak around 17 years (Romine and Reynolds, 2005). Over this period, functional neural networks develop and task-specific patterns of activation supporting cognitive performance increase (Adleman et al., 2002; Rubia et al., 2006). The decreased activity in the immature systems of children could be interpreted as reduced accessibility to the regions or to the computational abilities that support complex behaviour (Luna et al., 2010). This lower activation during cognitive tasks may result in a lower impairment of the cognitive processes when activated over time, similarly to what occurs with exercise-induced peripheral fatigue (Ratel et al., 2006).

HR and RPE increased linearly throughout the Yo-Yo IR1 in both conditions but were higher at iso-time in the mental fatigue condition. This finding is surprising as previous investigations have reported similar HR responses in the mental fatigue and control conditions (Smith et al., 2016). Moreover, HR at the beginning of the Yo-Yo IR1 was similar between the two conditions. Therefore, it is difficult to determine why HR was higher in the control condition during the Yo-Yo IR1. However, the elevated RPE in the mental fatigue condition is consistent with previous investigations (van Cutsem et al., 2017). According to the psychobiological model of endurance performance, athletes stop their exercise when they perceive effort to be very high or maximal (Marcora, 2008). A physiological explanation for the higher perception of effort during intermittent exercise in mentally fatigued conditions has recently been proposed and is probably related to the increase in the concentration of adenosine in the extra-cellular space (Martin et al., 2018).

Contrary to previous research in adult soccer players (Smith et al., 2016), the present study shows that mental fatigue impairs soccer-specific technical performance only in U18 (and only for LSPT), but not in U14 and U16 players. This could be related to our aforementioned discussion about the development of brain areas underlying response inhibition and, in general, cognitive function. Given this hypothesis, it could be possible that mental fatigue would impair technical performance less in U14 and U16 than in U18. Moreover, given the lower technical and physical ability of young football players, we did not discount any shots of the LSST (based on shot speed or shot sequence time). When discounting shots that took more than 8.5 s to complete and/or were struck less than 64 $km \cdot h^{-1}$, as suggested by Ali and colleagues (Ali et al., 2007), U14 and U16 performance time and penalty time remain just above the level of significance set in this study (0.051 – 0.059). Although our analysis does not align with that of Ali and colleagues (Ali et al., 2007), enforcing adult thresholds on youth players is unrealistic. Therefore, future studies could investigate technical performances in young soccer players using specific tests for the different age-groups.

Practical applications

This study on the effects of mental fatigue on physical and technical performance of soccer players suggests that mental fatigue may have a negative impact on physical (and partially technical) performance during a soccer match or training in young athletes. Mental fatigue may contribute to the previously identified negative impacts of “match-related fatigue” (Rampinini et al., 2008). Therefore, cognitive training aimed at building a resistance to mental fatigue may be beneficial (Slimani et al., 2016). Associating traditional with cognitive workouts that stimulate mental processes in soccer players could have a positive impact on performance during matches.

Limitations and future perspectives

Despite the new insight into mental efforts in young soccer players, this study presented some methodological limitations that should be considered when interpreting the results. Firstly, similar to most investigations in this area, the cognitive task was not specific to the demands of soccer. Therefore, although we can gain insight into whether mental fatigue may contribute to ‘match-related fatigue’ observed in young soccer players (Rampinini et al., 2008), impairments observed in this investigation cannot be directly translated into competition environments. Future studies may benefit from considering more soccer-specific fatiguing tasks (e.g. tactical video sessions, simulated press conferences), or fatiguing tasks more relevant to young cohorts (e.g. school classes). Secondly, we decided to use physical tests not specifically designed for young athletes. This choice was dictated by our aim to compare the results of a previous study conducted on adult soccer players (Smith et al., 2016), with a cohort of youth soccer players. We recommend future investigations consider tasks specific to the age groups being investigated. Finally, the only physiological measure that we considered was HR. Therefore, the unexpected change in HR during the Yo-Yo IR1 could not be double-checked with other physiological parameters.

Conclusions

Mental fatigue reduced soccer-specific physical performance in U14, U16 and U18 players.

Technical performance was unaffected by mental fatigue in the three age groups, except for LSPT in U18. These findings suggest that although mental fatigue affects youth soccer players, the impairments observed are not as substantial as previously observed in adult players. Nevertheless, youth coaches and players should attempt to avoid mental fatigue prior to competition, and implement strategies that attempt to reduce the negative impact of mentally demanding activity.

CHAPTER SIX

A 4-weeks endurance training program improves tolerance to mental exertion in untrained individuals

Filipas L, Martin K, Northey J, La Torre A, Keegan R, Rattray B. A 4-weeks endurance training program improves tolerance to mental exertion in untrained individuals. Journal of Science and Medicine in Sport. (Under review).

Abstract

Objectives: The aim of this study was to investigate whether 4 weeks of endurance training could improve tolerance to mental exertion in untrained participants. **Design:** Longitudinal training study. **Method:** Twenty participants completed a 4-week training protocol in a randomised and counterbalanced order. Baseline and follow-up assessment were conducted over three sessions in the week preceding and following the training period. During session 1, participants completed an incremental maximal ramp test. During sessions 2 and 3 participants completed a 15 min cycling time trial preceded by either a mental exertion or control task (counterbalanced). Following baseline assessments, participants were randomised into a physical training or placebo group that completed the training intervention thrice weekly over four weeks. **Results:** The physical training resulted in increases in VO_2peak relative to the placebo group ($b = 3.8$ ml·min^{-1}·kg^{-1}; 95 % confidence interval (CI): 1.6 to 6.0; $p = 0.003$). Linear mixed models utilising the control task time trial performance as a covariate found the physical training group increased their time trial distance following the mental exertion task to a greater extent than the placebo group ($b = 264$ m; 95 % CI: 211 to 476; $p = 0.03$). RPE during the time trial and perceptual measures of mental exertion did not significantly change between groups (all $p > 0.10$) although interaction effects were observed when considering the RPE-power output relationship during the time trial. **Conclusions:** Four weeks of endurance training increased tolerance to mental fatigue in untrained participants. This finding suggests that the ability to tolerate mental exertion is trainable and highlights the far-reaching benefits of endurance training.

Introduction

Endurance exercise training results in adaptations to the neuromuscular, metabolic, cardiovascular, respiratory and endocrine systems as reflected in improvements in key parameters of aerobic fitness, exercise economy and lactate/ventilatory threshold (Jones and Carter, 2000). Aside from these traditional, peripherally-based adaptations, endurance exercise is linked to cognitive benefits (Etnier et al., 1997; Gomez-Pinilla and Hillman, 2013) as well as structural (Wood et al., 2016) and functional changes in the brain (Pensel et al., 2018). These observations appear consistent with adaptations that, among other benefits, would confer improved efficiency and/or capacity for mental work. Brain adaptations to physical training could therefore also be important in our resistance to mental fatigue.

Acute mental fatigue is defined as a psychobiological state that may arise during or after prolonged cognitive activities; it is characterized by feelings of tiredness or exhaustion, and a decreased commitment and increased aversion to continue the current activity (Boksem and Tops, 2008). Acute mental fatigue has an adverse effect on cognitive function (Lorist et al., 2005; van der Linden et al., 2003) and endurance performance (van Cutsem et al., 2017). Mental fatigue appears to impair endurance performance through an increased perception of effort during subsequent physical exercise (van Cutsem et al., 2017). However, a physiological reason for an increase in perceived exertion has, to date, only been postulated (Martin et al., 2018). Beyond the physiological mechanism of mental fatigue, it is important to understand whether the ability to resist mental fatigue is relatively stable (e.g., associated with a genetic predisposition) or displays a trainable phenotype. In a recent study, we observed an impairment of endurance performance (measured as distance covered during a cycling time trial) after mental exertion in recreational and under 23 but not in professional cyclists (Filipas et al., 2019; Martin et al., 2016). In addition, the professional cyclists performed better during the cognitive challenge than recreational athletes, suggesting a potential association between resistance to mental fatigue and cognitive capacity in this context. This observational snapshot of cohorts does not, however, distinguish between heritability and trainability.

To date, no studies have investigated the effect of endurance training on the ability to tolerate mental exertion. Therefore, the primary aim of this study was to determine whether 4 weeks of endurance training could improve tolerance to mental exertion, as determined by subsequent time trial cycling performance, in previously untrained participants. We also sought to investigate if this physical training would have a measurable impact on cognitive function. The physical training group was compared to a placebo intervention group that watched a series of documentaries with recall questions to replicate the contact time of the training group, but not the physical demands.

Methods

Twenty initially untrained participants completed the study. Although twenty-two originally volunteered, two participants withdrew due to personal reasons after the first visit. Participants confirmed that they were not involved in regular vigorous physical activities (≤ 2.5 hours of moderate/vigorous physical activity per week) and completed a pre-exercise screening (Exercise and Sport Science Australia Adult Pre-Exercise Screening Tool) before entering the study. Participants were excluded if they declared any medical condition or injury that would prohibit them from completing the physical components of the study, had a diagnosed sleep disorder, known colour-vision impairments, or were shift-workers. The study design and procedures were approved by the University of Canberra Human Research Ethics Committee (HREC-2018-76) and followed the ethical principles for medical research involving human participants set by the World Medical Association Declaration of Helsinki. Participants were provided with written instructions outlining the procedures and risks associated with the study and gave informed written consent.

A randomised counterbalanced design was used. Group, and order of the experimental treatments, mental exertion or control task, were randomly assigned based on balanced permutations generated by a web-based computer program. While participants were aware of their allocation to the physical training or placebo group, they were blinded to the true aims of the study. Participants were told the study sought to compare the effects of a physical and a mental training program on cycling time trial performance.

An overview of the experimental protocol is shown in Figure 6.1.

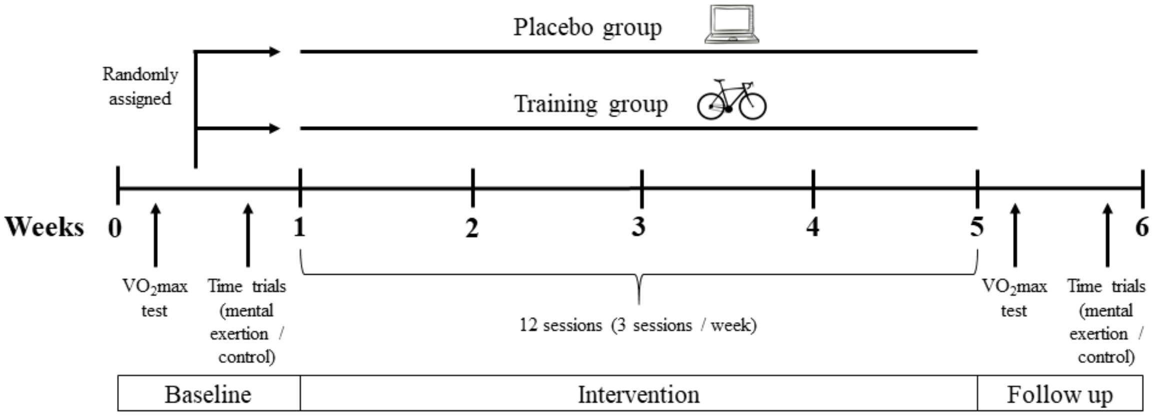

Figure 6.1. Schematic of the 6-week experimental design.

Participants attended the laboratory on eighteen occasions over six weeks. During baseline (week 1) and follow up (week 6), participants completed the same three sessions. During the first session, weight and height were assessed before participants completed an incremental maximal test on an SRM cycle ergometer (High-Performance Ergometer, Schoberer Rad MeBtechnik, Germany) to determine peak oxygen consumption and HR. The test began with a 3 min stage at 50 W, then increased by 25 W every minute to volitional exhaustion. Participants were then familiarised with the procedures and measures employed during the next two sessions.

During the second and third visits of the baseline and follow up sessions, participants completed the mental exertion task on one occasion, and the control task on the other occasion, in a randomised counterbalanced order. During the mental exertion task, participants completed a cognitive task which aimed to assess cognitive performance, induce a state of mental fatigue, and provide manipulation checks. This task consisted of 90 min of computerised cognitive tasks presented on a laptop using specialist software (E-Prime, Psychology Software Tools Inc., United States). The task was divided into three parts: a) an initial 45-min cognitive battery assessing cognitive domains including working memory, response inhibition and task-switching; b) a 40-min modified incongruent Stroop colour-word task (Martin et al., 2016); and c) 5-min of the same task-switching (flanker) task as in the cognitive battery. The 45-min cognitive battery comprised four different tasks: 1) 15-min of the flanker task (Eriksen and Eriksen, 1974); 2) 10-min of a go/no-go task (Nieuwenhuis et al., 2004); 3) 10-min of a 2-back task (Jaeggi et al., 2010), and; 4) 10-min of a working memory task (Vogel et al., 2005). For all tasks, participants were instructed to respond as quickly and accurately as possible. Cognitive tasks were completed with participants sitting comfortably in an air-conditioned, quiet room. Participants were familiarised with the cognitive battery and the Stroop task for 10 min each during the first visit. In addition, a standardized practise period (not analysed) was built into each cognitive test prior to the beginning of the data collection period, to ensure participants fully understood the instructions. Mean accuracy and reaction time of the correct responses were initially calculated in 5 min blocks for the flanker tasks and the Stroop task, and 4 min blocks for the go/no-go task, the 2-back task and the working memory task (the practices were excluded). Overall mean values were calculated for each block of the cognitive test. For the go/no-go task, the number of commission errors were defined as the total number of times participants responded to 'no-go' cues. Omission errors were also calculated and defined as the total number of times participants withheld responses on the 'go' trials. For the Stroop task, false alarms were detected when the reaction time was identified to be less than 200 ms.

Similarly, lapses were identified by responses over 2000 ms. Reaction time after an error was also calculated for the Stroop task. After the mental exertion task, participants recorded their subjective sensation of mental fatigue and motivation toward the upcoming physical endurance test using a VAS. Participants marked their response on a 10 cm line anchored by 0 (no mental fatigue at all) and 100 (maximal mental fatigue), and 0 (no motivation at all) and 100 (maximal motivation) for the mental fatigue and motivation scales respectively. Participant responses were measured from the left anchor and expressed in mm. Participants recorded subjective workload of the mental exertion task using the NASA-TLX (Hart and Staveland, 1988). Participants completed the NASA-TLX immediately after the other perceptual scales.

During the control task participants watched a white screen for 15 min. At the end of the task, they were required to record their subjective sensations of mental fatigue, motivation and workload, as described following the mental exertion task.

Within 10 min of the completion of the mental exertion and control tasks participants performed a 3 min standardised cycling warm-up followed by a 15 min time trial using an SRM cycle ergometer. The ergometer was setup to replicate the participants' preferred bike position in the initial session and replicated thereafter. Participants were instructed to cover as much distance as possible during the 15 min. A timer was placed in front of participants and remained visible during the time trial. Participants were blinded to all other performance and physiological data. A member of the research team who was blind to the experimental treatment received by the participants provided standardised verbal encouragement during the time trial. HR was recorded at the end of the warm-up, and during the final 15 s of every 3rd minute throughout the time trial using a HR monitor. At the same time points, RPE was recorded using the Borg 6-20 scale (Borg, 1982). Mean values for power, speed and cadence were calculated for each 3 min block of the time trial, and the total distance calculated using the speed recorded by the ergometer.

For both the physical training and placebo groups, the intervention took place during weeks 2-5 (lasting 4 weeks). The physical training group completed 3 x 60 min sessions per week on an air-braked cycle ergometer (Wattbike Pro Trainer, Wattbike Ltd, United Kingdom). Each week training consisted of: a) 1 x 60 min at 65-70 % of the peak HR recorded during the incremental maximal ramp test; b) 1 x 20 min at 65-70 %, plus 6 x 3 min at 85-90 % of the peak HR, with 2 min of active rest between repetitions; and c) 1 x 20 min at 65-70 % followed by 40 min at 75-80 % of the peak HR. During each session, HR, power output and cadence were recorded, and participants provided a session RPE (Table 6.1).

Table 6.1. Heart rate, power output, cadence and RPE for each session of training of the training group.

Session	Heart rate, bpm	Power output, W	Cadence, rpm	RPE
1	126 (8)	71.8 (20.2)	71.0 (6.2)	13.2 (2.4)
2	141 (6)	81.4 (20.7)	72.4 (8.4)	14.7 (2.0)
3	146 (8)	88.1 (25.4)	72.0 (9.6)	15.5 (2.6)
4	129 (7)	74.1 (17.6)	70.8 (8.1)	13.0 (2.4)
5	143 (5)	83.6 (20.3)	71.8 (5.9)	14.3 (2.0)
6	146 (9)	91.2 (28.1)	73.1 (8.3)	15.1 (2.5)
7	127 (7)	81.1 (20.1)	72.6 (9.3)	11.9 (1.0)
8	142 (5)	85.9 (21.9)	72.7 (6.4)	13.4 (1.6)
9	146 (8)	94.3 (26.5)	73.7 (9.3)	14.1 (3.4)
10	128 (7)	79.5 (19.5)	71.5 (11.1)	11.6 (1.2)
11	142 (5)	90.1 (24.0)	73.8 (6.7)	13.6 (2.1)
12	145 (10)	99.8 (27.8)	75.1 (8.9)	14.5 (3.0)

Note: Data are presented as mean (SD)

The placebo group attended the laboratory on the same number of occasions and for the same duration as the physical training group. However, participants watched an assortment of documentaries lasting approximately 50-60 min sourced from local free-to-air broadcasting. The documentaries were viewed by the research team prior to the start of the study and were chosen so that they were interesting but not likely to generate strong emotive responses. To ensure that the participants attended to the documentary, at the end of each viewing participants were asked to answer four simple questions pertaining to the content of each video (participants' maximum mistake rate was 1 out 4).

All the testing and intervention sessions were performed in an isolated air-conditioned room (20 ± 1 °C). Prior to each visit, participants were instructed to sleep for at least 7 h, refrain from the consumption of alcohol and caffeine, and avoid any vigorous exercise the day before visiting the laboratory. Participants were also instructed to avoid any mentally demanding tasks on the day of the training and testing sessions. Each participant carried out the sessions individually and at the same time of day (within 1 h period, between 9:00 and 13:00).

Statistical analysis was conducted with R version 3.4.2 (R Core Team, 2013). The mean and SD of the outcome measures at baseline and follow up were calculated for each group. Group differences in baseline characteristics were assessed with Chi-square tests for categorical data and t-tests for continuous data. To investigate intervention effects, data were analysed by General Linear Mixed Models with a random intercept fitted for participants to take into account the repeated measures nature of the data and interindividual variability using the lme4 package (Bates et al., 2014). For each model, the dependent variable was the outcome measured during the mental exertion task. The independent variables were time (baseline and follow up) and group (training and placebo) with the corresponding control task outcome as a covariate.

The interaction terms between group and time were included in each model. A significant interaction term indicated the change from baseline to follow up was different by group. Visual inspection of QQ-plots generated for each model showed no obvious deviations from normality. Statistical significance was accepted at $p < 0.05$.

Results

Participants were similar between groups at baseline regarding anthropometric characteristics, VO_{2peak} and distance covered during the time trial (Table 6.2).

Table 6.2. Baseline characteristics of the study sample by group allocation.

	Training group (n = 10)	Placebo group (n = 10)	p
Females, n (%)	7 (70)	7 (70)	1.00
Age, y	27.6 (6.3)	27.5 (6.0)	0.97
Height, cm	169.4 (6.8)	169.5 (9.6)	0.98
Weight, kg	69.6 (18.4)	68.7 (14.3)	0.91
VO_{2peak}, $ml \cdot min^{-1} \cdot kg^{-1}$	32.9 (6.9)	32.8 (5.6)	0.98
TT in control condition, m	6823 (715)	6762 (701)	0.85

Note: Data are presented as mean (SD) or number of participants.

At baseline, participants completed significantly less distance following the mental exertion task compared to the control task (mean diff: -223 m; 95 % CI: -137 to -309; $p < 0.001$). Using the NASA-TLX scale, participants reported that the mental exertion task was more mentally demanding (mean diff: 6.4; 95 % CI: 5.5 to 7.4; $p < 0.001$) than the control task. The VAS scales showed mental fatigue (mean diff: 53 mm; 95 % CI: 42 to 65; $p = 0.001$) was significantly greater, while motivation (mean diff: -3 mm; 95 % CI: -12 to 7; $p = 0.55$) was not significantly different, following the mental exertion task compared to the control task.

There was a group*time interaction for VO_{2peak} (F (18,1) = 11.29; p = 0.003), such that the physical training group improved significantly more than the placebo group (b = 3.8 $ml \cdot min^{-1} \cdot kg^{-1}$; 95 % CI: 1.6 to 6.0).

The primary outcome measure was time trial distance following the mental exertion task. Distance covered in the control task was included in the model as a covariate to account for differences in time trial performance between groups following the intervention period. There was a significant group*time interaction (F (19,1) = 5.66; p = 0.03; Figure 6.2) and examination of the fixed effects showed the physical training group improved time trial distance in the mental exertion task significantly more than the placebo group (b = 264 m; 95 % CI: 211 to 476).

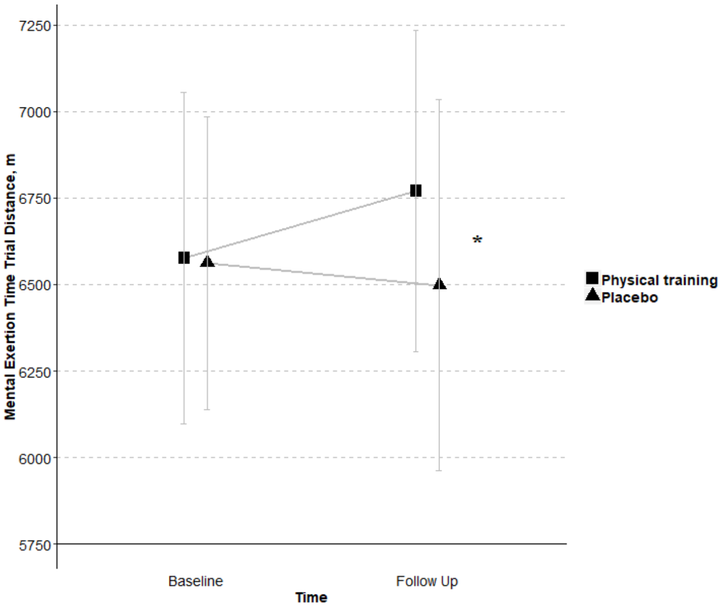

Figure 6.2. Time trial distance during the mental exertion condition. The change in control condition time trial distance was subtracted from the post intervention data to reflect the inclusion of this variable as a covariate in the Linear Mixed Models. Physical training group improved time trial distance in the mental exertion task significantly more than the placebo group. Data are presented as mean ± 95 % Confidence Intervals.

RPE, power, and power relative to RPE, measured at each 3-min split during the time trial following mental exertion was then investigated (Figure 6.3). To account for the structure of this data, time trial split was initially included in the models as a three-way interaction with group and time, with the control task outcomes included as a covariate. Non-significant interaction terms were dropped from the final models for ease of interpretation. Firstly, there were no significant group*time*split interactions for RPE, power or power relative to RPE (all $p > 0.70$). For RPE there were no significant two-way interaction effects (all $p > 0.20$). For power, the physical training group improved during the mental exertion time trial to a greater extent than the placebo group (group*time: F (181,1) = 20.86; $p < 0.001$; b = 16.12 W; 95 % CI: 8.76 to 22.82). Finally, the physical training group increased power relative to RPE at iso-time (group*time: F (179,1) = 39.91; $p < 0.001$; b = 1.60 W/RPE; 95 % CI: 1.08 to 2.08) to a greater extent than the placebo intervention, indicating that participants in the physical training group produced a higher power output for the reported RPE following the mental exertion task.

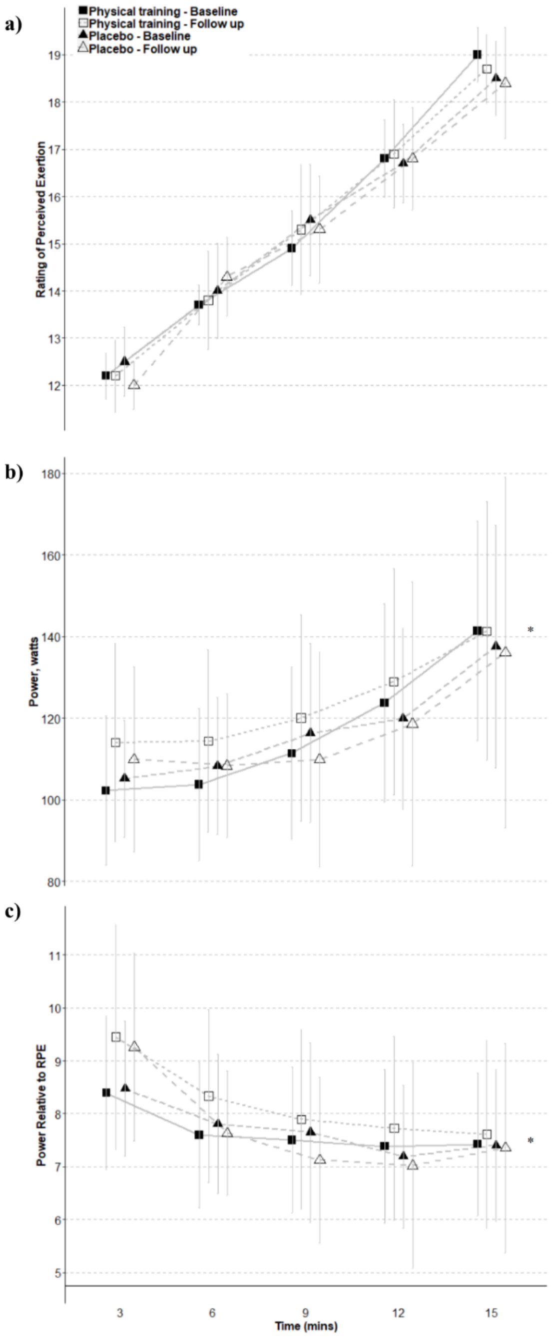

Figure 6.3. RPE (a), power (b) and power relative to RPE (c) during the mental exertion condition for the physical training and placebo groups. The change in control condition time trial outcomes was subtracted from the post intervention data to reflect the inclusion of this variable as a covariate in the Linear Mixed Models. Physical training group improved power and power relative to RPE in the mental exertion task significantly more than the placebo group. Data are presented as mean ± 95 % Confidence Intervals.

For the NASA-TLX scale, there were no significant group*time interactions for the mental demand (F (18,1) = 2.20; p = 0.16), temporal demand (F (18,1) = 1.39; p = 0.25), physical demand (F (18,1) = 1.98; p = 0.18), performance (F (18,1) = 0.05; p = 0.81), effort (F (18,1) = 0.04; p = 0.85), or frustration (F (18,1) = 0.16; p = 0.69) subscales. For the VAS, there were no significant group*time interactions for sensation of mental fatigue (F (17,1) = 1.17; p = 0.29) or motivation (F (18,1) = 0.54; p = 0.47) prior to completing the time trial in the mental exertion task.

There were no significant group*time interactions for the cognitive performance outcomes (Table 6.3).

Table 6.3. Mean (SD) accuracy, reaction time and specific errors for the different tasks of the cognitive battery in training and control groups at baseline and follow up.

	Task	Training group - Baseline	Control group - Baseline	Training group - Follow up	Control group - Follow up
Accuracy (%)	Flanker (1)	98.2 (1.5)	96.3 (3.2)	98.4 (1.5)	97.3 (4.2)
	Go/no-go	98.7 (2.0)	98.5 (1.2)	98.5 (1.2)	98.4 (0.9)
	2-back	94.4 (2.3)	93.9 (3.9)	94.8 (3.4)	92.4 (4.3)
	Working memory	77.1 (10.6)	74.9 (12.7)	82.1 (9.6)	81.2 (12.9)
	Stroop	94.9 (2.0)	94.8 (4.5)	97.0 (2.1)	96.7 (1.8)
	Flanker (2)	98.8 (1.3)	97.1 (2.8)	98.2 (2.1)	96.2 (3.8)
Reaction time (ms)	Flanker (1)	423 (49)	429 (64)	413 (38)	427 (57)
	Go/no-go	813 (98)	857 (104)	825 (90)	866 (101)
	2-back	572 (150)	604 (144)	600 (179)	614 (107)
	Working memory	681 (136)	709 (112)	682 (167)	652 (79)
	Stroop	819 (167)	811 (125)	812 (161)	769 (145)
	Flanker (2)	430 (52)	454 (49)	419 (42)	429 (65)
Other measures	Go/no-go omission	1.9 (2.9)	1.6 (1.1)	2.7 (1.9)	3.6 (2.4)
	Go/no-go commission	0.4 (0.5)	0.3 (0.7)	0.4 (1.0)	0.2 (0.6)
	Stroop false alarms	1.5 (4.4)	0.9 (1.3)	0.1 (0.3)	0.8 (1.1)
	Stroop	6.9 (10.9)	5.3 (5.6)	4.4 (7.9)	3.3 (4.1)

lapses				
Stroop reaction time (post error)	933 (237)	918 (153)	908 (202)	797 (144)

Discussion

The main finding of this study was that a 4-week physical endurance training program increased tolerance to mental exertion, showing an improved physical performance after a mental exertion task compared to a placebo group. Further, power output during the time trial was higher for the reported RPE after the intervention period in the mental exertion task condition, suggesting central as well as peripheral adaptations to the physical training. No other differences were found between the physical training and placebo groups for other perceptual or cognitive performance measures.

As expected, the endurance training protocol was effective in improving VO_2peak and performance in the cycling time trial. This improvement was accompanied by an increase in mental exertion tolerance in the physical training group, reflected in an almost negligible time trial performance decrement after the mental exertion task following the physical training intervention. In the placebo-based intervention the mental exertion task-induced a similar reduction in time trial performance at both time points. To our knowledge, our study is the first to show that a physical endurance training program can increase resilience to prior mental exertion. We suggest that given subjective reports of mental fatigue did not change, that is, participants still reported high mental fatigue scores after the mental exertion task, this result reflects an increased tolerance to mental exertion. Increased tolerance to mental exertion may come about through the pursuit of effortful tasks, such as endurance training. Indeed, cognitive control is often used to describe the processes, or capacity, by which individuals manage goal-orientated behaviours against distractions, disincentives, habitual tendencies or in the face of many choices (Badre and Nee, 2018; Norman and Shallice, 1986), and is thought to increase with the pursuit of effortful behaviours. Unfortunately, we did not record how effortful participants perceived the different interventions, but a change in tolerance appears apparent and could be supported mechanistically within our results. We observed an increase in the power output relative to RPE in the physical training group during the training protocol and the time trials. Whereas this may just reflect peripheral adaptations to the physical training stimulus, the physical training group increased power relative to RPE at iso-time following the mental exertion task relative to placebo suggesting that central adaptations were also generated. We have previously proposed (Martin et al., 2018) how adenosine-reducing changes in cerebral fuel stores (e.g., Matsui et al, 2012) and/or neural recruitment patterns (e.g., Chong et al., 2018), perhaps reflecting altered mental efficiency, could account for this increased tolerance. Hence there are possible physiological mechanisms that may explain our data suggesting that - at least to some extent - resilience to mental exertion is a trainable trait. Our recent research seems to support this hypothesis, showing that tolerance to mental exertion is higher in elite athletes than in recreational ones, but also that sub-elite athletes have an intermediate ability to tolerate mental exertion compared to elite and recreational (Filipas et al., 2019; Martin et al., 2016).

We found no change in cognitive performance in our untrained, although cogntivively functioning participants. There is minimal support for physical training improving cognitive performance in young healthy adult populations (e.g., a 4-month endurance training stimulus, Stroth et al., 2010), with most research supporting the role of physical activity in either cognitive development during childhood (Fedewa and Ahn, 2011), or maintaining function with older age (Colcombe and Kramer, 2003; Northey et al., 2018). Thus, the lack of impact on cognitive performance from our relatively short intervention is consistent with existing trends.

Limitations and future perspectives

A possible limitation of this study was that we chose to include a placebo intervention which replicated the time spent by the training group, but not the physical demands. In doing so however, we were conscious that cognitive and/or emotional control effort may have its own training effect and thus chose relatively emotionally neutral, although reasonably interesting content. Although we believe this met the aim of creating a placebo, we did not ask participants their expectations, nor about the effort required for either intervention (outside RPE in the physical training group).

Future studies could confirm our findings using more demanding or prolonged cognitive tasks, or technologies such as electroencephalography to evaluate changes in neural processing and not just overt behavioural outcomes.

Conclusions

Four weeks of endurance training increased tolerance to mental exertion in untrained participants with relative subjective ratings suggesting that central changes may account for this improvement. Cognitive performance assessments were however unable to find any changes following endurance training in this study.

CHAPTER SEVEN

Main findings and final considerations

Main findings

The present thesis aimed to describe the effects of mental fatigue on sport-specific physical and technical performance, focusing on possible age-specific differences. Study 1 (chapter three) examined the effect of mentally demanding cognitive tasks on rowing performance in prepubertal athletes. Results revealed that rowing time trial performance was not affected by mental fatigue. In addition, physiological and perceptual measures recorded during the physical task remain unchanged after mental fatigue. Study 2 (chapter four) analyzed the effect of a mentally demanding response inhibitory task on time trial performance in sub-elite under 23 cyclists. Results showed that mean power output and cadence were negatively affected by the task, whereas HR, RPE, blood lactate concentration, and HRV did not change after the task. Study 3 (chapter five) investigated the effects of mental fatigue on soccer-specific physical and technical performance in young players of three different age-groups. In this study, mental fatigue significantly reduced physical performance in the three age groups, alongside an increase in HR and RPE, without alteration of technical performance, except for passing test in U18 players. Study 4 (chapter six) investigated whether 4 weeks of endurance training could improve tolerance to mental exertion in untrained participants. Results revealed that physical training group increased their time trial distance following the mental exertion task to a greater extent than the placebo group. RPE during the time trial and perceptual measures of mental exertion did not significantly change between groups although interaction effects were observed when considering the RPE-power output relationship during the time trial.

Limitations

The limitations of each specific study are reported directly in the discussion section of each study. In general, a conclusive explanation for some controversial results of the present study (e.g., the effect of mental fatigue in young soccer players, but not in young rowers) is still missing and further investigation are needed to try to give a final response to some questions that arise from the present research project.

Conclusions

This thesis provides insight into the effects of mental fatigue on sport-specific physical and technical performance, focusing on possible age-specific differences. This thesis delivers novel insight into the different responses to mental fatigue based on the age and fitness-level of the participants. In addition, this thesis provides some proofs supporting the trainability hypothesis of the tolerance to mental fatigue.

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