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ORIGINAL ARTICLE

Mental fatigue does not affect maximal anaerobic exercise performance

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Abstract
Purpose Mental fatigue can negatively impact on submaximal endurance exercise and has been attributed to changes in perceived exertion rather than changes in physiological variables. The impact of mental fatigue on maximal anaerobic performance is, however, unclear. Therefore, the aim of the present study was to induce a state of mental fatigue to examine the effects on performance, physiological and perceptual variables from subsequent tests of power, strength and anaerobic capacity.
Methods Twelve participants took part in the single-blind, randomised, crossover design study. Mental fatigue was induced by 90 min of the computer-based Continuous Performance Task AX version. Control treatment consisted of 90 min of watching emotionally neutral documentaries. Participants consequently completed countermovement jump, isometric leg extension and a 3-min all-out cycling tests.
Results Results of repeated measures analysis of variance and paired *t* tests revealed no difference in any performance or physiological variable. Rating of perceived exertion tended to be greater when mentally fatigued (mental fatigue $= 19 \pm 1$ vs control $= 18 \pm 1$, $p = 0.096$, $\eta_p^2 = .232$) and intrinsic motivation reduced (mental fatigue $= 11 \pm 4$ vs control $= 13 \pm 6$, $p = 0.063$, $d = 0.597$) in the mental fatigue condition.
Conclusions Near identical responses in performance and physiological parameters between mental fatigue and control conditions suggest that peripheral mechanisms primarily regulate maximal anaerobic exercise. Whereas mental fatigue can negatively impact submaximal endurance exercise, it appears that explosive power, voluntary maximal strength and anaerobic work capacity are unaffected.

Keywords Mental fatigue · Peripheral · Power · Strength · Anaerobic capacity

Abbreviations

3MT	Three-minute all-out cycle test
ANOVA	Analysis of variance
AX-CPT	Continuous performance test AX version
CMJ	Countermovement jump
CON	Control
EMG	Electromyography
MF	Mental fatigue
POMS	Profile of mood states
RPE	Rating of perceived exertion
RSME	Rating scale of mental effort
SIMS	Situational intrinsic motivation scale

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Introduction

Mental fatigue is a change in psychobiological state, caused by prolonged periods of demanding cognitive activity (Marcora et al. 2009). This change is gradual and cumulative and has subjective and objective manifestations including increased resistance against further effort (Meijman 2000), changes in mood (Holding 1983) and feelings of 'tiredness' and 'lack of energy'. Mental fatigue can be brought about by sustained performance of a single cognitive task but can also include different tasks that require mental effort, such as work related fatigue. It is well known that mental fatigue negatively affects cognitive performance (Boksem et al. 2005; Boksem and Tops 2008; van der Linden et al. 2003); however, only recently has it been observed that mental fatigue impacts on subsequent exercise performance (Brownsberger et al. 2013; Marcora et al. 2009; Pageaux et al. 2013, 2014). For example, mental fatigue reduced time to exhaustion during both high-intensity (80 % of peak power output) cycling (Marcora et al. 2009) and a prolonged isometric leg extension (target torque of 20 % maximal voluntary contraction) (Pageaux et al. 2013). Average running speed was decreased in a 5-km time trial (Pageaux et al. 2014) and mental fatigue lowered self-regulated power output during ergometer cycling, when participants were instructed to sustain effort corresponding to descriptors from Borg's 6–20 Rating of Perceived Exertion (RPE) (Borg 1982) scale of fairly light (RPE of 11) and hard (RPE of 15) (Brownsberger et al. 2013).

Despite the relatively consistent observation that mental fatigue impairs subsequent endurance performance, the mechanism behind this effect is presently unknown. Previous studies have revealed no difference in any physiological variable between mental fatigue and control conditions. Variables that were previously thought to limit exercise performance, for example heart rate, cardiac output, oxygen consumption or lactate during cycling to exhaustion (Marcora et al. 2009), neuromuscular function during a prolonged isometric leg extension (Pageaux et al. 2013) and pacing strategy in a 5-km running time trial (Pageaux et al. 2014) were unaffected by mental fatigue. Despite the lack of physiological differences between conditions, poorer performances were observed in the experimental trial. Subsequently the negative impact of mental fatigue on performance has been attributed to the greater perceived exertion experienced by participants when mentally fatigued (Marcora et al. 2009; Pageaux et al. 2013, 2014). Prolonged mental exertion is hypothesised to directly affect the cortical centres involved in the cognitive aspect of central motor command (Hallett 2007) and the primary sensory input for perceived exertion (Marcora et al. 2009). Specifically, the anterior cingulate cortex (ACC), an area of the prefrontal cortex strongly activated by tasks requiring cognitive effort (Paus et al. 1998), is believed to be affected by mental fatigue. The ACC has shown correlation between changes in activation and changes in RPE during manipulations of exercise intensity under hypnosis and motor imagery (Williamson et al. 2001, 2002, 2006), and rats with experimental ACC lesions engage significantly less than normal rats in tasks requiring physical effort to obtain a larger reward (Rudebeck et al. 2006; Walton et al. 2003, 2006). Furthermore, experimental evidence from in vitro and animal studies suggest that neural activity increases extracellular concentrations of adenosine (Lovatt et al. 2012) and that brain adenosine induces a reduction in endurance performance (Davis et al. 2003).

While the effect of mental fatigue on endurance performance appears clear, the impact on maximal anaerobic exercise performance is unknown. Rozand et al. (2014a) observed no change in maximal muscle activation or isometric elbow flexion torque following either a mental training session (using imagined maximal isometric elbow flexion contractions), or a combined physical and mental training session (using both imagined and actual maximal contractions). No change in performance occurred despite greater perceived mental fatigue in the mental training sessions, relative to the physical session alone. In contrast, (Bray et al. 2012) observed a linear decrease in force production during 4 s maximal voluntary handgrip contractions, when completed intermittently between 3 min of an incongruent Stroop task. However, the study of (Bray et al. 2012) consisted of a number of methodological flaws that may account for the differences in observations. For example, in the central fatigue review by Gandevia (2001), a number of guidelines were provided to ensure participants exerted a true maximal effort during maximal voluntary contractions. Among the guidelines was the use of visual feedback to maximise voluntary effort. Feedback was not provided by (Bray et al. 2012). Furthermore, Rozand et al. (2014b) demonstrated that completion of a modified incongruent Stroop task did not affect maximal force capacity of the knee extensors when completed intermittently between the cognitive tasks. Where maximal anaerobic tasks are predominantly regulated by peripheral fatigue such as availability of metabolic substrates (Coggan and Coyle 1991), accumulation of metabolites (Fitts 1993) and impairments in neuromuscular transmission (Balog et al. 1994), endurance tasks are additionally altered by central fatigue, a reduction in central motor drive (Amann 2011). Given the differences in mechanisms of fatigue between exercise tasks, it is possible mental fatigue affects these two types of activity differently.

Exercise tasks of short duration and maximal intensity utilizing explosive power, strength and the anaerobic work capacity are of interest as they are critical to many competitive events. For example, high-intensity activity in soccer has been found to be related to the overall success of the team (Di Salvo et al. 2009; Rampinini et al. 2007), explosive strength training improved 5 km running performance in well-trained endurance athletes (Paavolainen et al. 1999) and anaerobic power of the leg and arm muscles are believed to determine success in wrestling (Hübner-Wozniak et al. 2004). These sporting events have traditionally been thought to be limited by anaerobic energy depletion, accumulation of metabolic by-products or failure of the muscle fibre contractile mechanisms. Therefore, the aim of the present study was to investigate the impact of prolonged mental exertion leading to mental fatigue, on subsequent maximal anaerobic exercise. Mental exertion consisted of 90 min of a cognitively demanding computer task requiring sustained attention, working memory, response inhibition and error monitoring (Carter et al. 1998). Explosive power, maximal strength and anaerobic work capacity were assessed using a countermovement jump (CMJ), isometric leg extension and a 3-minute all-out cycling test (3MT). Given previously mental fatigue has not impacted on peripheral mechanisms of fatigue or induced any extent of central fatigue, authors hypothesised that prolonged mental exertion would not impact upon the performance of maximal anaerobic exercise tasks.

Methods

Participants

Twelve participants (7 men and 5 women; age 23 ± 3 years and peak oxygen uptake 53 ± 13 l min^{-1}, gas exchange threshold 2.6 ± 0.7 l min^{-1}) gave informed consent, for the study protocol approved by the University of Canberra Committee for Ethics in Human Research. Eligibility included being aged between 18 and 40 years, free from any known disease or injury, a non-smoker and not taking any medication with the exception of contraceptives. All participants were involved in high-intensity training at least three times per week. High-intensity activity included training and competition for field-based team sports or high-intensity interval training included in triathlon training programs. Participants had no history of sleep disorders and were not shift workers. During the experiment participants were naive to the precise aim and hypothesis. Participants were led to believe the study was examining whether watching television or completing a mentally engaging task is good preparation for maximal anaerobic exercise performance. At the end of the final visit, participants were debriefed and asked not to discuss the study with other participants.

Study design and procedures

A single-blind, randomised, crossover study design was employed. Testing took place on five occasions. The first testing session consisted of an incremental ramp protocol to determine resistance for the 3MT. The second and third session acted as familiarisation trials. These trials mimicked what occurred in the physical testing portion of the experimental and control trials. During these trials participants were also familiarised with the questionnaires and scales used in subsequent sessions. During the fourth and fifth testing sessions participants completed the Profile of Mood States (POMS) questionnaire prior to completing baseline CMJ and isometric leg extensions. Participants then undertook either the experimental or control trial. Treatment order was randomly allocated according to balanced permutations generated by a web-based computer program (http://www.randomization.com). Following the treatment or control sessions, participants completed a post-treatment POMS, Rating Scale of Mental Effort (RSME) and Situational Motivation Scale (SIMS). Participants then completed five minutes of unloaded warm-up on the cycle ergometer followed by supervised static and dynamic stretching of the lower limbs. Cadence was monitored and kept consistent between trials. Three minutes of static stretching was followed by ten leg swings, ten body weight squats and ten lunges. The warm-up was consistent between all tests and trials. Following the warm-up participants completed three CMJ, three maximal isometric leg extensions and the 3MT. A 3-min recovery was allowed between the final CMJ and the leg extension and the leg extension and the 3MT. Testing on all occasions was performed in the same order. A schematic of the study design is represented in Fig. 1. A single, consistent researcher was present at all testing sessions and provided encouragement

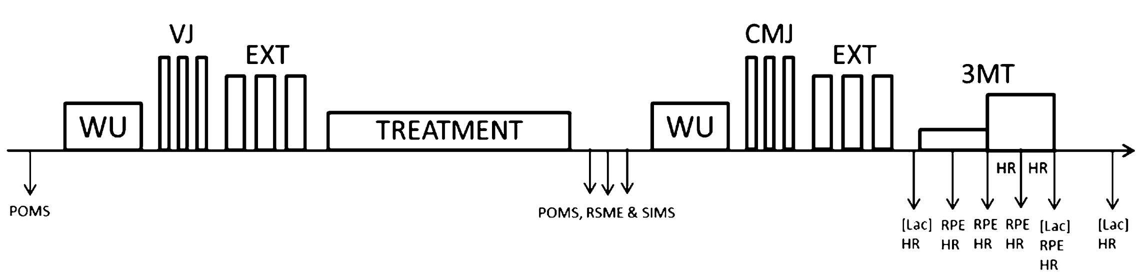

Fig. 1 Schematic of experimental session 3 and 4. *WU* warm up, *CMJ* countermovement jump, *EXT* isometric leg extension, *3MT* 3 min all out cycle test, *POMS* profile of mood states, *RSME* rating scale of mental effort, *SIMS* situational intrinsic motivation scale, *[lac]* plasma lactate concentration, *HR* heart rate, *RPE* rating of perceived exertion

at regular intervals during each of the exercise tasks. An effort was made to maintain consistency of the content and delivery of the encouragement.

Participants were given written instructions to arrive at the laboratory fully hydrated, to have slept for at least 7 h the night before, refrained from the consumption of alcohol, and to have avoided any vigorous exercise 24 h prior to all testing. Participants were also instructed to avoid any caffeine for at least 3 h before testing. Finally, participants were instructed to record their food intake at breakfast and to repeat the recorded intake before the following testing session and to eat at the same time. All testing sessions were conducted at the same time of day, for each individual, on each occasion. Participants completed testing sessions over a period of 5 weeks, with a minimum 48 h recovery between visits. Environmental conditions in the laboratory were kept consistent and the same lead researcher was present for all trials. Throughout each session only water was consumed.

Mental fatigue treatment

The mental fatigue treatment consisted of 90 min of a modified version of the computer-based Continuous Performance Test AX-version (AX-CPT). A version of this task has been used previously to induce a state of mental fatigue (Marcora et al. 2009; Pageaux et al. 2013). The current version utilised all letters of the alphabet as distractor letters, opposed to the two distractor letters in the aforementioned task. Continuous performance tests are associated with significant activation of the anterior cingulate cortex (Riccio et al. 2002), an area of the prefrontal cortex affected by mental fatigue (Lorist et al. 2005). In this version of the task, letters are visually presented one at a time in a continuous fashion on a computer screen. Participants were instructed to respond with a right mouse press whenever the stimulus included an X that was preceded by an A. The left mouse button was pressed for all other stimuli, including an X that was not preceded by an A, and any other letter. Letter sequences were presented in pseudorandom order, such that 20% of the stimuli were targets (A–X). The remaining letters of the alphabet served as non-targets. All letters were presented centrally in black ink, on a white background for duration of 200 ms each. The inter-trial interval varied across trials and was 1.5, 2 or 2.5 s (including the duration of the stimulus). Inter-trial interval was randomised across the task. Practice trials were allowed and the participant was trained in the correct performance of the test before formal testing was initiated. To further increase engagement and motivation in the AX-CPT, a $50 prize was awarded for the best five performances in terms of both correct detections and reaction time. Because increased reaction time is a well-established effect of mental fatigue (Boksem et al. 2005; Marcora et al. 2009), the speed and proportion of correct responses to the AX trials during the first and last 15 min period of the AX-CPT were compared as a manipulation check.

Control treatment

Control treatment consisted of watching "World Class Trains—The Venice Simplon Orient Express" and "The History of Ferrari—The Definitive Story" for 90 min on the same computer used for the mental fatigue treatment. The documentaries were chosen based on topics capable of maintaining a neutral mood and stable heart rate (Silvestrini and Gendolla 2007). During both treatments, the lead researcher observed participants throughout the 90 min to ensure compliance.

Physical performance

An incremental ramped protocol was conducted on a cycle ergometer set in hyperbolic mode (High Performance Ergometer, Schoberer Rad MeBtechnik, Germany) to determine the workload for the 3MT. The ergometer seat and handlebars were adjusted for comfort and participants' own pedals fitted if required. Geometric setup of the ergometer was consistent between tests and trials. The ramp protocol consisted of five minutes of unloaded baseline pedalling, followed by a ramped increase in power output of 30 W per minute until volitional exhaustion. Participants were instructed to maintain their preferred cadence (≈70–100 rpm) for as long as possible. The test was terminated when the pedal rate fell to more than 10 rpm below the chosen cadence for more than 10 s, despite strong verbal encouragement.

Vertical jump performance consisted of a countermovement jump. No attempts were made to standardise the amplitude or rate of the countermovement; rather participants were encouraged to self-select these variables with the view to obtaining maximum jump height. The power, velocity and acceleration variables of the CMJ were recorded using the GymAware optical encoding system (Kinetic, Mitchell, Australia), with the linear position transducer attached to the right side of a wooden dowel rod and placed on the upper portion of the scapula region of the participant's back. The bar maintained contact with the body at this position, by the participant placing their hands on the bar and pulling it into their body. The retraction tension of the linear position transducer was 5 N, which was adjusted for calculating peak power, velocity and acceleration. Displacement time data were sampled at 29 kHz and down sampled to 50 Hz where position points were time stamped when a change in position was detected, with time between samples limited to a minimum of 20 ms. Each participant performed five consecutive trials with a 15-s standing recovery between each jump. The first two trials were used as warm-up. Participants were instructed to jump as high as possible from a standing start. Only the best jump for each participant was used in data analysis. Eccentric displacement, concentric peak velocity, peak force and mean power were analysed between conditions due to their sensitivity to neuromuscular fatigue (Taylor et al. 2012). Height of the jump was recorded as a performance measure.

Leg strength was assessed by an isometric maximal knee extension of the right leg only using an isokinetic dynamometer (KinCom; Kinetic Communicator, Chattecx, Chattanooga, TN). Participants were seated in a rigid chair and firmly strapped at the hip and distal thigh. The rotational axis of the dynamometer was visually aligned to the lateral femoral epicondyle, and the lower leg was attached to the dynamometer lever arm just above the medial malleolus. The hip, thigh and lower leg were firmly attached to the chair and lever arm, respectively, while the foot was free to move around the ankle joint. The individual positioning for each participant of the seat, backrest, dynamometer head and lever arm length was kept consistent for all testing. The geometric setup of the dynamometer was completed by the same researcher on each occasion. Isometric contractions were performed in a seated position with a 90° flexion angle at both the hip and knee. Following two submaximal warm-up contractions, each participant performed three, 6 s knee extensions at maximal effort. Each 6 s effort was interspersed with 30 s passive recovery. Participants were instructed to contract "as forcefully as possible". Visual feedback of the instantaneous dynamometer force was provided to the participants on a computer screen. Peak and mean torque, time to peak torque and time to half peak torque were recorded.

The 3MT was used to assess anaerobic work capacity. It is a test requiring an initial maximal effort which is then followed by a significant drop-off in power output as the participant experiences significant fatigue. The test requires considerable effort, motivation and commitment by the participant. The test has been used as a method of deriving critical power from a single exercise bout (Vanhatalo et al. 2007). Critical power represents the highest sustainable work rate (Vanhatalo et al. 2007), while the maximum amount of work that can be performed above critical power is often referred to as anaerobic work capacity (Morton 2006). The 3MT has also been shown to result in a reproducible power output profile (Burnley et al. 2006). The test begins with 3 min of unloaded baseline pedalling at a self-selected cadence, this cadence was noted and repeated in subsequent trials, and participants were then asked to increase their cadence during the last five seconds of the baseline period, followed by an all-out 3-min effort. Resistance for the 3MT was derived in accordance with the original investigators' procedures (Burnley et al. 2006). In brief, the linear mode of the ergometer was used so that participants would attain a power output halfway between their gas exchange threshold and peak oxygen uptake, on reaching their preferred cadence. Gas exchange threshold and peak oxygen uptake were derived from the incremental ramp test. During the 3MT, participants were not aware of the elapsed time to prevent pacing and strong verbal encouragement was provided throughout the test by the same lead researcher. To ensure an all-out effort, participants were instructed to maintain their cadence as high as possible at all times. Mean and peak power values, critical power and anaerobic work capacity were recorded for each trial. Critical power was calculated as the average power output for the final 30 s of the test, and the anaerobic work capacity was calculated as the power–time integral above critical power (Vanhatalo et al. 2007). Cadence and pacing profiles were established as means over twelve time points.

Physiological measures

Oxygen uptake during the ramp protocol was recorded using an open-circuit indirect calorimetry system (True-One 2400 Metabolic Measurement System, Parvo Medics, USA). Oxygen uptake was recorded to determine peak oxygen uptake and gas exchange threshold to establish individual workloads for the subsequent 3MT. Peak oxygen uptake was determined as the highest oxygen uptake recorded over a 10-s period. Data was reduced to 10 s averages for the estimation of the gas exchange threshold using the V-slope method (Beaver et al. 1986). Capillary blood samples were collected from a fingertip on the left hand prior to the warm-up of the 3MT, 10 s following termination and 4 min post. Samples were analysed using a lactate analyser (Lactate Pro, Arkay, Japan). These samples were used to compare plasma lactate concentration between treatments and over time. Heart rate was recorded during the incremental ramp test and the 3MT with a heart rate monitor fitted by a chest strap (T34 Non-Coded Heart Rate Transmitter, Polar, Finland). Heart rate was recorded every minute during the incremental ramped test and every 30 s during the 3MT.

Perceptual measures

Mood states were assessed using the POMS inventory. The POMS inventory contains 65 adjectives rated on a five-point scale (0 = not at all, 4 = extremely) designed to measure tension, depression, anger, vigour, fatigue and confusion, as well as provide a global mood state score (McNair et al. 1985). POMS has been well established in terms of validity and reliability (McNair et al. 1985) and is used widely in research with clinical and normal populations, including in the exercise domain (Snow and LeUnes 1994). The subscales of fatigue and vigour were of particular interest in this study.

The RSME was used to measure the subjective mental workload of each treatment (Zijlstra 1993). The RSME was presented as a single continuum on a sheet of paper with validated reference points along the scale. Participants were asked to mark on the vertical line, how much cognitive effort they had to invest in the task, within the scale anchored by written indicators of 'not at all effortful' to 'very effortful'. The distance of the mark from the baseline was measured in millimetres. This single-dimension scale has good sensitivity to mental workload (Verwy and Veltman 1996).

The SIMS was used to assess participants' motivation towards the upcoming physical tasks (Guay et al. 2000). The SIMS is a 16-item self-report inventory, which is designed to measure intrinsic motivation, identified regulation, external regulation and amotivation. Intrinsically motivated behaviours are those that are engaged in for the pleasure and satisfaction derived from performing them (Deci 1971). Identified regulation occurs when behaviour is valued and perceived as being chosen by oneself; however, the motivation is still extrinsic because the activity is not performed for itself but as a means to an end (Guay et al. 2000). External regulation occurs when behaviour is regulated by rewards or to avoid negative consequences (Guay et al. 2000). Extrinsic motivation pertains to a wide variety of behaviours where the goals of action extend beyond those inherent in the activity itself (Guay et al. 2000). Each item was rated on a 7-point Likert scale (1 = corresponds not at all, 7 = corresponds exactly). Scores were calculated for each individual subscale. Reliability and construct validity have been established for the SIMS and found suitable for both field and laboratory settings (Standage et al. 2003).

Perceived exertion during the 3MT was assessed using the Borg 6–20 scale (Borg 1970). The term perceived exertion was defined as a subjective rating of exertion, based on the physical sensations a person experiences during exercise. Participants were instructed to rate whole body perceived exertion at the midway point of the warm-up and during the last 15 s of each minute of the 3MT. Perceived exertion was rated on a large scale placed in front of participants at the appropriate time point. Each participant was instructed to rate the overall sensation of how strenuous the exercise was, with no attempt made to distinguish between sensations such as pain, effort and discomfort. A rating of 6 was to correspond to sensations associated with being at rest and a rating of 20 as sensations experienced with the hardest exercise participants had ever completed. Participants were further requested to 'not think too much', and to pick the number on the scale which best described how they felt. Administration of all of the scales was completed in the same order on each occasion.

Statistical analysis

All data are presented as mean ± standard deviation. Paired *t* tests were used to assess the effect of condition (mental fatigue vs control) on 3MT performance measures, subjective workload and motivation. A paired *t* test was also used to compare the proportion of correct detections and reaction time between the first and last 15 min of the AX-CPT. Repeated measures analysis of variance (ANOVA) were used to assess the effect of condition and time using two time points for mood, CMJ and leg extension variables, three time points for lactate concentration, four time points for RPE, eight time points for heart rate and twelve time points for cadence and pacing profiles. When the sphericity assumption was violated, the Greenhouse-Geisser correction was employed. Significance was set at 0.05 (2-tailed) for all analyses. Effect size for paired *t* tests were calculated as Cohen's d, using the small = 0.2, medium = 0.5 and large = 0.8 interpretation (Cohen 1992). Effect size for each repeated measures ANOVAs were calculated as partial eta squared (η_p^2), using the small = 0.02, medium = 0.13 and large = 0.26 interpretation (Bakeman 2005).

Results

Mental fatigue

The proportion of correct detections was not different from the first to the last 15 min of the mental fatigue treatment ($p = 0.152$, $d = 0.445$). Reaction time tended to increase from the beginning to the end of the AX-CPT although not significant (from 484 ± 81 to 511 ± 99 ms, $p = 0.095$, $d = 0.527$). Cognitive effort was rated as greater following the AX-CPT, relative to control (Mental fatigue, MF = 71.7 ± 18.7 vs. Control, CON = 26.0 ± 23.1, $p < 0.001$, $d = 1.994$). Vigour decreased and fatigue increased over time in both conditions (Vigour: $p < 0.001$, $\eta_p^2 = 0.794$ and Fatigue: $p = 0.015$, $\eta_p^2 = 0.431$) but there was no condition or interaction effect (Vigour: $p = 0.970$, $\eta_p^2 < 0.001$ and $p = 0.385$, $\eta_p^2 = 0.069$ and Fatigue: $p = 0.385$, $\eta_p^2 = 0.069$ and $p = 0.358$, $\eta_p^2 = 0.077$).

Physical performance

There was no difference between conditions during the 3MT for peak power (MF = 689 ± 298 vs CON = 700 ± 301 W, $p = 0.412$, $d = 0.246$), mean power (MF = 298 ± 79 vs CON = 294 ± 77 W, $p = 0.217$, $d = 0.378$), critical power (MF = 238 ± 55

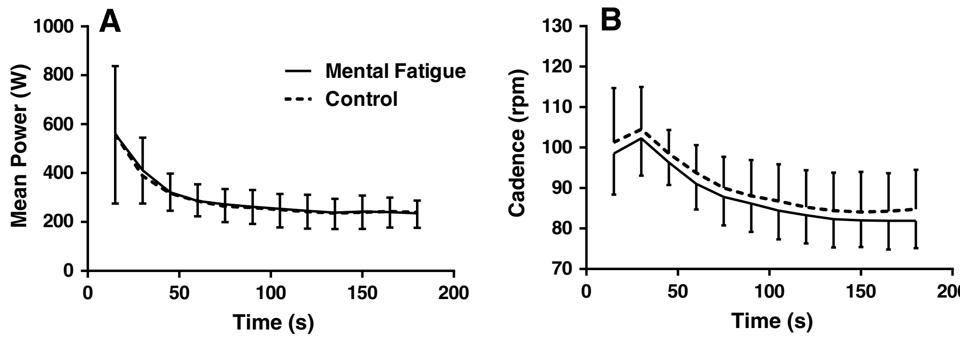

Fig. 2 Mean power output profile (**a**) and time course of cadence (**b**) for mental fatigue and control condition. Data are presented as mean ± SD

Table 1 Change in countermovement jump and isometric leg extension performance variables from baseline to post treatment, and between conditions

Variable	Control-pre	Control-post	MF-pre	MF-post
Countermovement jump				
Mean power (W)	2,537 ± 920	2,566 ± 1001	2,558 ± 979	2,647 ± 957
Peak force (N)	2,041 ± 542	1,977 ± 539	2,071 ± 563	2,051 ± 683
Concentric peak velocity (m s^{-1})	3.06 ± 0.43	3.07 ± 0.48	3.08 ± 0.47	3.13 ± 0.53
Eccentric displacement (m)	0.51 ± 0.12	0.52 ± 0.13	0.52 ± 0.12	0.54 ± 0.13
Jump height (m)	0.40 ± 0.09	0.39 ± 0.09	0.41 ± 0.07	0.39 ± 0.08
Isometric leg extension				
Peak torque (Nm)	244 ± 61	248 ± 48	239 ± 81	249 ± 87
Mean torque (Nm)	216 ± 55	248 ± 48	215 ± 76	223 ± 81
Time to half peak torque (s)	0.32 ± 0.27	0.35 ± 18	0.32 ± 0.26	0.36 ± 0.23
Time to peak torque (s)	3.08 ± 1.12	2.96 ± 0.99	2.75 ± 1.26	2.62 ± 0.83
Peak torque slope (Nm s^{-1})	173 ± 86	147 ± 78	168 ± 116	224 ± 80

No variable was significantly different between time points or conditions

vs CON = 242 ± 64 W, $p = 0.537$, $d = 0.184$) or estimated anaerobic work capacity (MF = 9.4 ± 5.9 vs CON = 8.0 ± 2.9 kJ, $p = 0.315$, $d = 0.304$). The group mean responses to the 3MT are shown in Fig. 2. When the time data were expressed as 15 s averages and compared, cadence was not different between conditions ($p = 0.176$, $\eta_p^2 = 0.711$), but there was a main effect of time ($p < 0.001$, $\eta_p^2 = 0.159$). Specifically cadence was significantly reduced from each 15 s time bin from 45 to 120 s. Power output was also not different between conditions ($p = 0.195$, $\eta_p^2 = 0.147$), but showed a main effect for time ($p = 0.001$, $\eta_p^2 = 0.634$). Power output was reduced from 15 to 75 s. There was no interaction effect for cadence or power output. Similarly, there was no difference for any recorded variable pre to post treatment or between conditions during the CMJ or isometric leg extension (Table 1).

Physiological measures

Heart rate and lactate concentration increased over time (HR: $p < 0.001$, $\eta_p^2 = 0.948$ and Lactate: $p < 0.001$, $\eta_p^2 = 0.959$), but there was no condition or interaction effect (HR: $p = 0.441$, $\eta_p^2 = 0.055$ and $p = 0.350$, $\eta_p^2 = 0.089$ and Lactate: $p = 0.847$, $\eta_p^2 = 0.004$ and $p = 0.980$, $\eta_p^2 = 0.002$).

Perceptual measures

Identified regulation (MF = 14 ± 5 vs CON = 16 ± 5, $p = 0.201$, $d = 0.392$), external regulation (MF = 10 ± 8 vs CON = 10 ± 8, $p = 0.809$, $d = 0.072$) and amotivation (MF = 8 ± 4 vs CON = 6 ± 2, $p = 0.222$, $d = 0.374$) were not different between conditions as determined by the SIMS. Intrinsic motivation tended to be reduced following the mental fatigue treatment, with a medium effect size (MF = 11 ± 4 vs. CON = 13 ± 6, $p = 0.063$, $d = 0.597$). The effect of mental fatigue on motivation is represented in Fig. 3. RPE increased over time in both conditions. Perceived exertion increased over time ($p < 0.001$, $\eta_p^2 = 0.928$) and although not significant, RPE tended to be greater when mentally fatigued, evidenced by the medium effect size (MF = 19 ± 1 vs CON = 18 ± 1, $p = 0.096$, $\eta_p^2 = 0.232$) (Fig. 4). There was no significant interaction effect between condition and time ($p = 0.803$, $\eta_p^2 = 0.20$).

Discussion

The primary finding of the present study was that a state of induced mental fatigue did not affect the performance of maximal anaerobic exercise tasks. Physiological variables

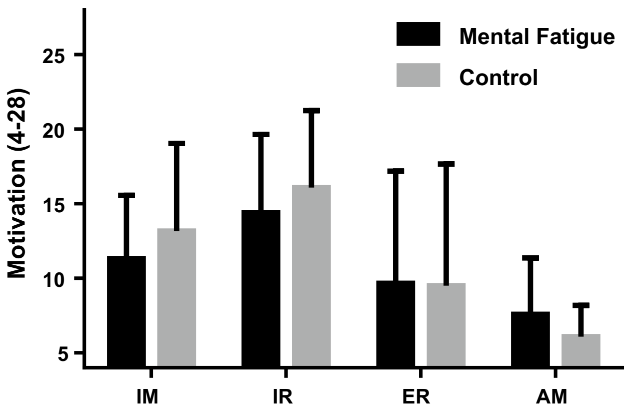

Fig. 3 Effect of condition on motivation. *IM* intrinsic motivation, *IR* internal regulation, *ER* external regulation, *AM* amotivation. Data are presented as mean ± SD

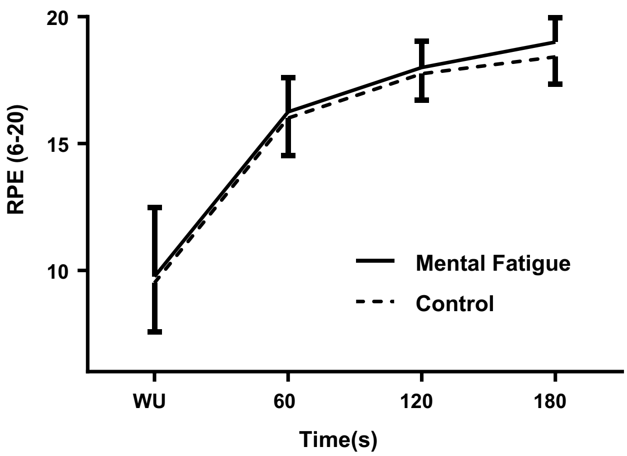

Fig. 4 Effect of mental fatigue on perception of effort during 3MT. Data are presented as mean ± SD

remained unchanged between experimental and control conditions, and despite a tendency for RPE to be greater and a tendency for intrinsic motivation to be reduced following the AX-CPT, measures of explosive power, voluntary maximal strength and anaerobic work capacity were not affected. Ninety minutes of the AX-CPT was successful in inducing a state of mental fatigue. This was evidenced by the trend for increased reaction time and greater rating of mental effort, compared to control.

None of the 3MT performance variables were different between mental fatigue and control conditions. The power output profile and the time course of cadence were near identical in both trials, suggesting central motor drive was unaffected by mental fatigue. Similarly, the lack of difference in estimates of critical power and anaerobic work capacity indicate that the energy contribution during the experimental condition was also unaffected by mental fatigue. From the outset of the 3MT (0–10 s), all participants produced peak power outputs followed by a consistent decline in performance before levelling off during the final 30 s. The comparable all-out pacing profile and inability to maintain force, the near maximal heart rate and RPE values, as well as the elevated plasma lactate concentration suggest maximal efforts were achieved on both occasions.

Performance during a CMJ and an isometric leg extension were also unaffected by mental fatigue. Countermovement jumps have been used previously to assess neuromuscular fatigue in athletes with the measures of eccentric displacement, mean power and peak velocity force during the concentric portion being notably sensitive to fatigue (Taylor et al. 2012). The present study, however, found no difference in any of these variables when mental fatigue was induced through prior mental exertion. Similarly, and consistent with the present findings, mental fatigue was reported to not induce changes in neuromuscular function of the knee extensor muscles (Pageaux et al. 2013; Rozand et al. 2014b) or elbow flexors (Rozand et al. 2014a). In all of these studies, however, muscle function was assessed using a single joint, isometric movement. Early researchers for instance suggested that among the processes affected by mental fatigue, is the coordination and accurate timing of tasks (Bartlett 1943). Mental fatigue does not seem to affect maximum strength (Bray et al. 2008; Pageaux et al. 2013); however, it has been observed that mental exertion has an effect on the electromyography (EMG) activation required to generate and sustain a submaximal force (Bray et al. 2008). Taken individually an increase in EMG activation may represent an increase in motor unit recruitment to carry out a movement. Several muscles, however, contribute to the production of an action, and when individual muscles are analysed, it cannot be determined whether an increase in EMG activation is representative of an increase in activation of the total muscle group or whether the increase of motor unit recruitment of one muscle is to supplement decreased activation of another. Individual muscles within a muscle group co-contract to stabilise a joint and create an efficient movement pattern (Ford et al. 2008). It is possible therefore, that if participants were required to complete a more complex, dynamic movement, mental fatigue may impact upon performance. The results of the present study, however, suggest no effect of mental fatigue on either a CMJ or knee extensor, isometric maximal strength test.

The disparity between the impact of mental fatigue on submaximal endurance exercise and maximal anaerobic exercise may lie in the performance characteristics of each task. Submaximal endurance exercise can be limited central fatigue, a progressive reduction in voluntary activation of muscle during exercise (Gandevia 2001), as well as altered by peripheral fatigue, fatigue produced by changes at or distal to the neuromuscular junction (Gandevia 2001). In contrast, during one-off maximal anaerobic tasks, peripheral fatigue plays the primary modulating role. Pacing is defined as the efficient use of energetic resources during athletic competition, so that all available energy stores are used before finishing a race, but not so far from the end of a race that a meaningful slowdown can occur (Foster et al. 2003). It has been suggested that pacing is regulated by the brain for prolonged endurance exercise (Noakes 2012), while short-duration maximal anaerobic tasks are less influenced by pacing strategy than metabolic fatigue. Although pacing strategy is still important for short-duration tasks, this usually only occurs when the initial power output is lower than is possible if the athlete is instructed to perform an all-out effort with no regard for overall performance (Nummela et al. 1992). As instructed, participants during the 3MT adopted an all-out approach, accelerating to peak power quickly and gradually decreasing power output with increasing duration. All-out pacing is characterised by the athlete working maximally from the start of the event and rapidly fatiguing as a result (Thompson 2014). With a reduced cognitive component of the exercise task, mental fatigue may influence performance less.

An increase in RPE has been observed consistently, and to a larger extent, in other studies where mentally fatigued participants completed exercise tasks of a longer duration and lower intensity than the 3MT (Brownsberger et al. 2013; Marcora et al. 2009; Pageaux et al. 2014). In the present study, RPE tended to be greater when mentally fatigued; however, this difference did not reach significance, nor did increased RPE impact on performance measures. Although the mechanisms behind the increase in perception of effort have yet to be fully elucidated, mental fatigue is believed to act on the anterior cingulate cortex (ACC), an area of the prefrontal cortex associated with error detection (Carter et al. 1998), decision making (Walton et al. 2006) and perception of effort during exercise (Williamson et al. 2001, 2002, 2006). During endurance exercise, RPE rises as a linear function of duration, reaching a maximum value at the termination of a maximal effort (Noakes 2012). During the 3MT the RPE response was curvilinear in nature with a rapid increase evident following the first minute when participants were attempting to maintain peak power output (unsuccessfully) in the face of rapidly developing fatigue. Whereas RPE during submaximal endurance exercise may indicate pacing strategy or exercise duration remaining (Crewe et al. 2008), the use of RPE during short-duration and maximal exercise tasks is less clear.

In the present study intrinsic motivation tended to be reduced when mentally fatigued, despite no change in performance. In considering the issue of quantifying motivation, the present study suggests that intrinsic motivation, but not other forms of motivation, may be reduced when mentally fatigued. In the absence of changes in physiological variables, this may suggest an integral role for intrinsic motivation in determining how performers respond to mental fatigue. Accordingly, intrinsic motivation is suggested as one key mechanism through which the effects of mental fatigue may be generated. Further, if supported, this finding would warrant serious attention when considering how to 'motivate' participants in fatigue and pacing studies, as cash prizes and normative comparisons have consistently been shown to undermine intrinsic motivation (Deci 1971, 1972; Vansteenkiste and Deci 2003). A number of previous studies have found no difference in motivation between mental fatigue and control conditions (Brownsberger et al. 2013; Marcora et al. 2009; Pageaux et al. 2013, 2014). Limitations of previous research, however, include measuring motivation as a single unit and not differentiating between types of motivation (Brownsberger et al. 2013; Marcora et al. 2009). By quantifying motivation in this simplified way, it is possible that any impact of mental fatigue on intrinsic motivation may have been concealed. Furthermore, motivation has been modified in previous studies, using external incentives to enhance performance of the physical tasks (Marcora et al. 2009; Pageaux et al. 2014). The results of the present study, however, suggest that it might be peripheral fatigue and types of motivation other than intrinsic motivation which modulated the 3MT exercise performance. Given the medium effect size of the change in perceptual measures, and no effect of mental fatigue on exercise performance, we suspect that under the conditions of the present study there are not likely to be any practical applications leading to changes in current behaviour. Future research should focus more closely on change in intrinsic motivation with mental fatigue.

Conclusions

Despite successfully inducing a state of mental fatigue, 90 min of the AX-CPT did not have any impact on the performance of a CMJ, a maximal isometric knee extension or a 3-min all-out cycling test. Physiological variables were unchanged between conditions and although RPE tended to be greater and intrinsic motivation reduced when mentally fatigued, this did not impact upon maximal anaerobic performance. The findings of the present study suggest that peripheral mechanisms primarily regulate this type of performance. Although previous research indicates that mental fatigue negatively influences submaximal endurance exercise, it seems that it does not impair maximal anaerobic exercise tasks.

Conflict of interest The authors declare that they have no conflict of interest.

Ethical standards The experiments conducted for the present manuscript comply with current laws of Australia.

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