

Mental fatigue impairs physical performance in humans

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Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. *J Appl Physiol* 106: 857–864, 2009. First published January 8, 2009; doi:10.1152/jappphysiol.91324.2008.—Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity. Although the impact of mental fatigue on cognitive and skilled performance is well known, its effect on physical performance has not been thoroughly investigated. In this randomized crossover study, 16 subjects cycled to exhaustion at 80% of their peak power output after 90 min of a demanding cognitive task (mental fatigue) or 90 min of watching emotionally neutral documentaries (control). After experimental treatment, a mood questionnaire revealed a state of mental fatigue ($P = 0.005$) that significantly reduced time to exhaustion (640 ± 316 s) compared with the control condition (754 ± 339 s) ($P = 0.003$). This negative effect was not mediated by cardiorespiratory and musculoenergetic factors as physiological responses to intense exercise remained largely unaffected. Self-reported success and intrinsic motivation related to the physical task were also unaffected by prior cognitive activity. However, mentally fatigued subjects rated perception of effort during exercise to be significantly higher compared with the control condition ($P = 0.007$). As ratings of perceived exertion increased similarly over time in both conditions ($P < 0.001$), mentally fatigued subjects reached their maximal level of perceived exertion and disengaged from the physical task earlier than in the control condition. In conclusion, our study provides experimental evidence that mental fatigue limits exercise tolerance in humans through higher perception of effort rather than cardiorespiratory and musculoenergetic mechanisms. Future research in this area should investigate the common neurocognitive resources shared by physical and mental activity.

exercise performance; endurance; perceived exertion; motivation

MENTAL FATIGUE is a psychobiological state caused by prolonged periods of demanding cognitive activity and characterized by subjective feelings of “tiredness” and “lack of energy” (9). The effects of mental fatigue on cognitive performance (7, 8, 14, 38, 41, 66–68) and the skilled performance of drivers and air pilots (25, 36) have been extensively investigated. An increasing number of studies are also revealing the neural alterations caused by prolonged periods of demanding cognitive activity in both health (8, 38, 39, 41, 64) and disease (14). On the contrary, the impact of mental fatigue on subsequent physical performance remains largely unknown. To the best of our knowledge, the only published observations date back to 1891 when Angelo Mosso reported in his seminal book on fatigue that muscle endurance was reduced in two fellow professors of physiology after long lectures and oral examinations (50).

The main aim of the present study was to confirm experimentally the hypothesis that mental fatigue impairs physical performance in humans. To test this hypothesis, we measured

tolerance to high-intensity cycling exercise after 90 min of the AX-continuous performance test (AX-CPT) (4, 12) in 16 healthy volunteers. This cognitive task requires sustained attention, working memory, response inhibition, and error monitoring (12), and it has been used previously to induce a state of mental fatigue (68). Importantly, the AX-CPT is associated with significant activation of the anterior cingulate cortex (ACC) (4, 12). This area of the prefrontal cortex is affected by mental fatigue (14, 39) and provides a neurobiological rationale for impaired performance in a subsequent physical task. In fact, ACC activity is related to perception of effort during exercise (72–74), and in animal studies, ACC lesions specifically affect effort-based decision making (57, 69, 70). According to the psychobiological model of exercise performance (42, 44) based on motivational intensity theory (76), these effects of mental fatigue may limit exercise tolerance independently of any cardiorespiratory and musculoenergetic alteration. However, fatigue-induced changes in ACC activity may also affect autonomic control (16, 72) and, thus, increase cardiovascular strain as demonstrated during mental tasks (75, 77). During intense cycling exercise, increased cardiovascular strain may lead to premature plateau or drop in cardiac output and reduced performance (23, 24, 48, 49). Therefore, we measured motivation related to the physical tasks, perceived exertion, and the main physiological factors associated with endurance exercise performance (6, 11, 31, 71), including cardiac output. These measurements should elucidate whether the hypothesized negative effect of mental fatigue on physical performance is mediated by psychobiological or cardiorespiratory and musculoenergetic mechanisms.

METHODS

Subjects and Ethical Issues

Sixteen eligible subjects [10 men and 6 women; mean \pm SD, age 26 ± 3 yr, height 175 ± 9 cm, weight 69 ± 10 kg, peak power output 288 ± 70 W, peak oxygen uptake ($\dot{V}O_{2\text{peak}}$) 52 ± 8 ml \cdot kg $^{-1}\cdot$ min $^{-1}$] signed an informed consent form describing the study protocol, which was approved by the Ethics Committee of the School of Sport, Health and Exercise Sciences (SSHES) according to the standards set by the Declaration of Helsinki. Eligibility criteria were being between 18 and 44 yr old, being involved in regular aerobic training, being free of any known disease, and not taking any medication with the exception of contraceptives.

All subjects were given written instructions describing all procedures related to the study but were naive of its aims and hypotheses. Participants believed that the study was on the effects of two different cognitive activities (a computerized task and watching television) on the physiological responses to exhaustive exercise. At the end of the last visit, subjects were debriefed, thanked for their participation, and asked not to discuss the study with other participants.

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Study Design and Procedures

For this study, we employed a single-blind, randomized, counter-balanced, crossover experimental design. Subjects visited the SSHES Physiology Laboratory on three different occasions. During the first visit, a preliminary incremental exercise test (2 min at 50 W + 50 W increments every 2 min) was performed until exhaustion [operationally defined as a pedal frequency of less than 60 revolutions/min (RPM) for more than 5 s despite strong verbal encouragement] on an electromagnetically braked cycle ergometer (Excalibur Sport, Lode, Groningen, The Netherlands) to measure $\dot{V}O_{2\text{peak}}$, and peak power output, which was calculated according to the equation of Kuipers et al. (35). The cycle ergometer was set in hyperbolic mode, which allows the power output to be set independently of pedal frequency over the range of 30–120 RPM. Before the incremental exercise test the position on the cycle ergometer was adjusted for each subject, and settings were recorded so that they could be reproduced at each subsequent visit. Subjects were also given standard instructions for overall rating of perceived exertion (RPE) using the 15-point scale developed by Borg (10). During the incremental exercise test, the scale low and high anchor points were established using the procedures described in detail by Noble and Robertson (51).

During the second visit, subjects were asked to fill in a mood questionnaire (see *Psychological Questionnaires* for details). After this questionnaire was completed, participants gave a 0.6- μ l sample of whole fresh blood from the right earlobe for assessment of glucose concentration (mmol/l) (ACCU-CHECK Aviva Blood Glucose Meter System, Roche Diagnostics, Mannheim, Germany). To reduce instrumentation time after treatment, the electrodes used for transthoracic bioimpedance analysis were also placed on the subject (see *Physiological and Perceptual Response to Exercise* for details). Participants then walked to an adjacent, quiet, dimly lit room with comfortable environmental conditions where one of two treatments was administered (see next section for details). Treatment order was randomly allocated according to balanced permutations generated by a web-based computer program (www.randomization.com). During treatment, heart rate (HR) was measured every 5 s using a telemetric monitor (Polar S610i, Polar Electro Oy, Kempele, Finland). After treatment, subjects returned to the laboratory and filled in the mood questionnaire for a second time, and a questionnaire on motivation related to the upcoming physical task (see *Psychological Questionnaires* for details). Another blood sample was taken to assess glucose concentration. Subjects were then positioned on the cycle ergometer set in hyperbolic mode, and instrumented for physiological measurements before starting the time-to-exhaustion test 15 min after the end of treatment. This high-intensity constant-power cycling test is sensitive to changes in endurance performance (2) and consisted of a 3-min warm-up at 40% of peak power output followed by a rectangular workload corresponding to 80% of peak power output. Pedal frequency was freely chosen between 60 and 100 RPM and was recorded every minute. Time to exhaustion was measured from the start of the rectangular workload until the pedal frequency was less than 60 RPM for more than 5 s despite standardized verbal encouragement (3) provided by a research assistant blind to treatment allocation. To increase motivation, we also offered cash prizes (£50 each) for the best cycling performance after each treatment. Physiological and perceptual responses were measured throughout the cycling test (see *Physiological and Perceptual Response to Exercise* for details). During the third visit, the same procedures were followed except for treatment, which was the opposite of the second visit.

All subjects were given written instructions to drink 35 ml of water per kilogram of body weight, sleep for at least 7 h, refrain from the consumption of alcohol, and avoid any vigorous exercise the day before each visit. Participants were also instructed to avoid any caffeine and nicotine for at least 3 h before testing. Finally, subjects were instructed to consume a set breakfast (2 slices of toast spread with margarine or butter, 250 ml of orange juice, and a banana) 1 h

before all testing sessions, which were conducted in the morning. At each visit to the lab, subjects were asked to complete a pretest checklist to ascertain that they had complied with the instructions given to them. Participants were also asked to declare if they had taken any medication/drug or had any acute illness, injury, or infection. Female participants were also asked how many days it was since their last menstruation. Each subject completed all testing sessions over a period of 2 wk with a minimum of 48 h recovery period between visits. Environmental conditions in the laboratory were kept between 18 and 22°C for temperature and 45 and 60% for humidity.

Treatment

Experimental treatment. We induced mental fatigue by having participants in the experimental condition work on the AX-CPT for 90 min. In this cognitive task (4, 12), sequences of letters were visually presented one at a time in a continuous fashion on a computer screen. Participants sat in front of a response box and were instructed to press the right button on target trials and the left button otherwise (button responses were reversed for left-handed people). Target trials were defined as a cue-probe sequence in which the letter A appeared as the cue and the letter X appeared as the probe. The remaining letters of the alphabet served as invalid cues and nontarget probes, with the exception of the letters K and Y, which were excluded because of their similarity in appearance to the letter X. Letter sequences were presented in pseudorandom order, such that target (AX) trials occurred with 70% frequency and nontarget trials occurred with 30% frequency. Nontargets were divided evenly (10% each) among the following trial types: BX trials, in which an invalid cue (i.e., non-A) preceded the target; AY trials, in which a valid cue was followed by a nontarget probe (i.e., non-X); and BY trials, in which an invalid cue was followed by a nontarget probe. To increase task difficulty, two white distractor letters (which could be any letter but A, K, X, or Y) were presented between the cue and probe, which were both red. All letters were presented centrally, on a black background, for a duration of 300 ms in 24-point uppercase Helvetica font. Each letter was followed by a 1,200-ms interval, which gives a 4,500-ms delay between the presentation of cue and probe stimuli. Any missed or incorrect response elicited a beep sound from two speakers as a prompt to increase speed and accuracy. To further increase engagement in the AX-CPT, a £50 prize was given for the best performance. Feedback on performance was presented on the computer screen every 30 min as a percentage of the maximum possible score. Performance was scored automatically by the computer on the basis of correct responses and response time. Because a reduction in vigilance and working memory are well-established effects of mental fatigue, the proportion of correct responses to the AX trials during the first and last 15-min period of the AX-CPT was compared as manipulation check.

Control treatment. Control treatment consisted of watching “World Class Trains—The Venice Simplon Orient Express” (Pegasus-Eagle Rock Entertainment, 2004) and “The History of Ferrari—The Definitive Story” (Boulevard Entertainment, 2006) for a total of 90 min in front of the same computer screen used for the AX-CPT. These themes were chosen based on the study by Silvestrini and Gendolla (61), who identified such topics as capable of maintaining a neutral mood and stable HR. During both treatments, one of the authors sat behind the subject to ensure compliance with treatment.

Physiological and Perceptual Response to Exercise

Oxygen uptake (l/min) and minute ventilation (l/min) during exercise were measured breath-by-breath using a computerized metabolic gas analysis system (MetaLyzer 3B, Cortex Biophysik, Leipzig, Germany) connected to an oro-(mouth) mask (7600 series, Hans Rudolph, Kansas City, MO). This automated device was calibrated before each test using certified gases of known concentration (11.5% O_2 and 5.1% CO_2) and a 3.0-liter calibration syringe (series 5530,

Hans Rudolph). All respiratory gas exchange data were averaged over 1-min periods before statistical analysis. At the end of warm-up, every 2 min during the rectangular workload, and 1 min after exhaustion, a 5- μ l sample of whole fresh blood was taken from the right earlobe and analyzed for lactate concentration (mmol/l) using a portable analyzer (Lactate Pro LT-1710, Arkray, Shiga, Japan). A transthoracic bioimpedance device (Physioflow PF05L1, Manatec, Petit-Ebersviller, France) was used to measure HR, stroke volume (SV), and cardiac output (CO) during exercise. Two sets of two electrodes (Ambu Blue Sensor VL, Ambu A/S, Ballerup, Denmark), one transmitting and the other one receiving a low amperage alternating electrical current, were applied on the supraclavicular fossa at the left base of the neck and along the xiphoid. Another set of two electrodes was used to monitor a single ECG lead in the V1/V6 position. All electrode placement areas were shaved if necessary, cleaned with an alcohol pad, and dried with a paper towel. Wires connected to the electrodes were fixed on the body using tape to reduce movement artifacts. Stroke volume (ml) is estimated by this computerized device from changes in transthoracic impedance during cardiac ejection according to the method described in detail by Charloux et al. (13). Cardiac output (l/min) was calculated as

$$CO = (HR \times SVi \times BSA)/1000$$

where BSA is body surface area (m^2) calculated according to the Haycock formula [$BSA = 0.02465 \times \text{body mass (kg)}^{0.5378} \times \text{stature (cm)}^{0.3964}$] and $SVi (ml/m^2) = SV/BSA$. Heart rate (min^{-1}) is based on the R-R interval determined from the first derivative of the ECG. These data were averaged over 1-min periods before statistical analysis. Accuracy of CO estimation with this noninvasive method has been validated against direct Fick methods (13). Furthermore, in a group of 20 healthy and fit men, reproducibility during intense cycling was high (coefficient of variation 3.4%) (30). Before each test, the Physioflow was autocalibrated using a procedure based on 30 consecutive heart beats recorded while the participant was resting in a seated position on the cycle ergometer, anthropometric data, and resting systolic and diastolic blood pressure values (mmHg) (13). These were the averages of two separate blood pressure recordings taken before and after the Physioflow autocalibration using an automated blood pressure monitor (Tango, SunTech Medical, Morrisville, NC). The Tango device was interfaced to the Physioflow by an analog cable for the ECG trigger. The size of the cuff, which was placed on the left arm of the subject, was based on individual arm girth. Blood pressure was also monitored at the end of warm-up and every 2 min during the rectangular workload. Mean arterial pressure (MAP) (mmHg) was calculated as $MAP = [(2 \times \text{diastolic}) + \text{systolic}]/3$. During the final 15 s of each minute of exercise, subjects were asked to rate how heavy and strenuous the exercise feels on a large RPE scale displayed in front of them throughout the cycling test. This scale ranges from 6 (no exertion at all) through 13 (somewhat hard) to 20 (maximal exertion).

Psychological Questionnaires

Mood. The Brunel Mood Scale (BRUMS) developed by Terry et al. (65) was used to assess mood. This questionnaire, which is based on the Profile of Mood States, contains 24 items (e.g., angry, uncertain, miserable, tired, nervous, energetic) divided into six respective subscales: anger, confusion, depression, fatigue, tension, and vigor. The items are answered on a 5-point Likert scale (0 = not at all, 1 = a little, 2 = moderately, 3 = quite a bit, 4 = extremely), and each subscale, with four relevant items, can achieve a raw score in the range of 0 to 16. Of particular interest in the present study were the subscales for fatigue and vigor.

Motivation. Motivation related to the time-to-exhaustion tests was measured using the success motivation and intrinsic motivation scales developed and validated by Matthews et al. (46). Each scale consists of 7 items (e.g., "I want to succeed on the task" and "I am concerned

about not doing as well as I can") scored on a 5-point Likert scale (0 = not at all, 1 = a little bit, 2 = somewhat, 3 = very much, 4 = extremely). Therefore, total scores for these motivation scales range between 0 and 28.

Statistical Analysis

All data are presented as means \pm SD. The effects of condition (mental fatigue vs. control) and time on vigor and fatigue (pretreatment vs. posttreatment), blood glucose (pretreatment vs. posttreatment), and each physiological and perceptual parameter at isotime [end of warm-up (0 min) + first 6 min of high-intensity cycling exercise] were tested using two-way fully repeated-measures ANOVAs. An isotime of 6 min was chosen to include all subjects in the analyses. When the sphericity assumption was violated, the Greenhouse-Geisser correction was employed. In case of a significant condition \times time interaction, simple main effects of condition were tested using the Holm-Bonferroni method (28).

The effect of condition on time to exhaustion was tested using the Hills-Harmitage approach (59), while the effects of condition on HR during treatment, motivation, average RPM, and physiological and perceptual parameters at exhaustion were analyzed using paired *t*-tests. A paired *t*-test was also used to compare the proportion of correct responses to the AX trials between the first and last 15-min periods of the AX-CPT. Significance was set at 0.05 (2-tailed) for all analyses, which were conducted using the Statistical Package for the Social Sciences, version 14.

RESULTS

Manipulation Checks

Average HR was significantly higher during the AX-CPT ($65 \pm 8 \text{ min}^{-1}$) compared with control treatment ($62 \pm 8 \text{ min}^{-1}$) ($P = 0.046$), while blood glucose declined from 5.6 ± 0.7 to $4.8 \pm 0.5 \text{ mmol/l}$ in both treatments (main effect of time, $P < 0.001$). The BRUMS questionnaire revealed a significant decrease in vigor (from 6.2 ± 3.1 to 3.5 ± 2.2) in both conditions (main effect of time, $P < 0.001$). However, fatigue increased significantly only after the AX-CPT (condition \times time, $P = 0.005$) (Fig. 1). Follow-up tests revealed no significant difference in fatigue pretreatment, but posttreatment fatigue was significantly higher compared with the control condition. This state of mental fatigue was associated with a significant decline in the proportion of correct responses to the

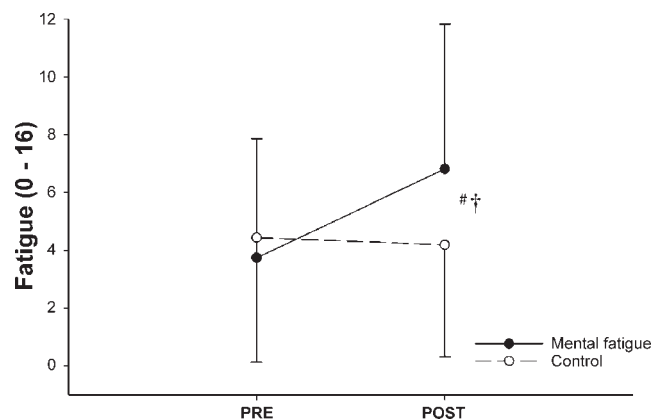


Fig. 1. Effect of treatment on self-reported fatigue. # Significant main effect of time ($P < 0.05$). †Significant condition \times time interaction ($P < 0.05$) and simple main effect of condition according to Holm-Bonferroni method. Data are presented as means \pm SD.

AX trials during the AX-CPT (first 15-min period $94.8 \pm 3.4\%$, last 15-min period $88.9 \pm 4.5\%$, $P < 0.001$).

Effect of Mental Fatigue on Exercise Tolerance

Average RPM during high-intensity cycling exercise was not significantly different between conditions (mental fatigue 83 ± 13 , control 84 ± 12). Time to exhaustion was significantly lower in the mental fatigue condition (640 ± 316 s) compared with control (754 ± 339 s) ($P = 0.003$) with no significant order effect ($P = 0.901$). Individual time to exhaustion was shorter in the mental fatigue condition in 13 of 16 subjects.

Effects of Mental Fatigue on Physiological Responses During Exercise

At isotime, all physiological variables changed significantly over time (all main effects of time, $P < 0.011$), but none of them was significantly affected by mental fatigue (Fig. 2). At exhaustion, both HR ($P = 0.007$) (Fig. 2A) and blood lactate ($P = 0.032$) (Fig. 2G) were significantly higher in the control condition compared with mental fatigue. None of the other physiological variables at exhaustion was significantly affected by prior demanding cognitive activity.

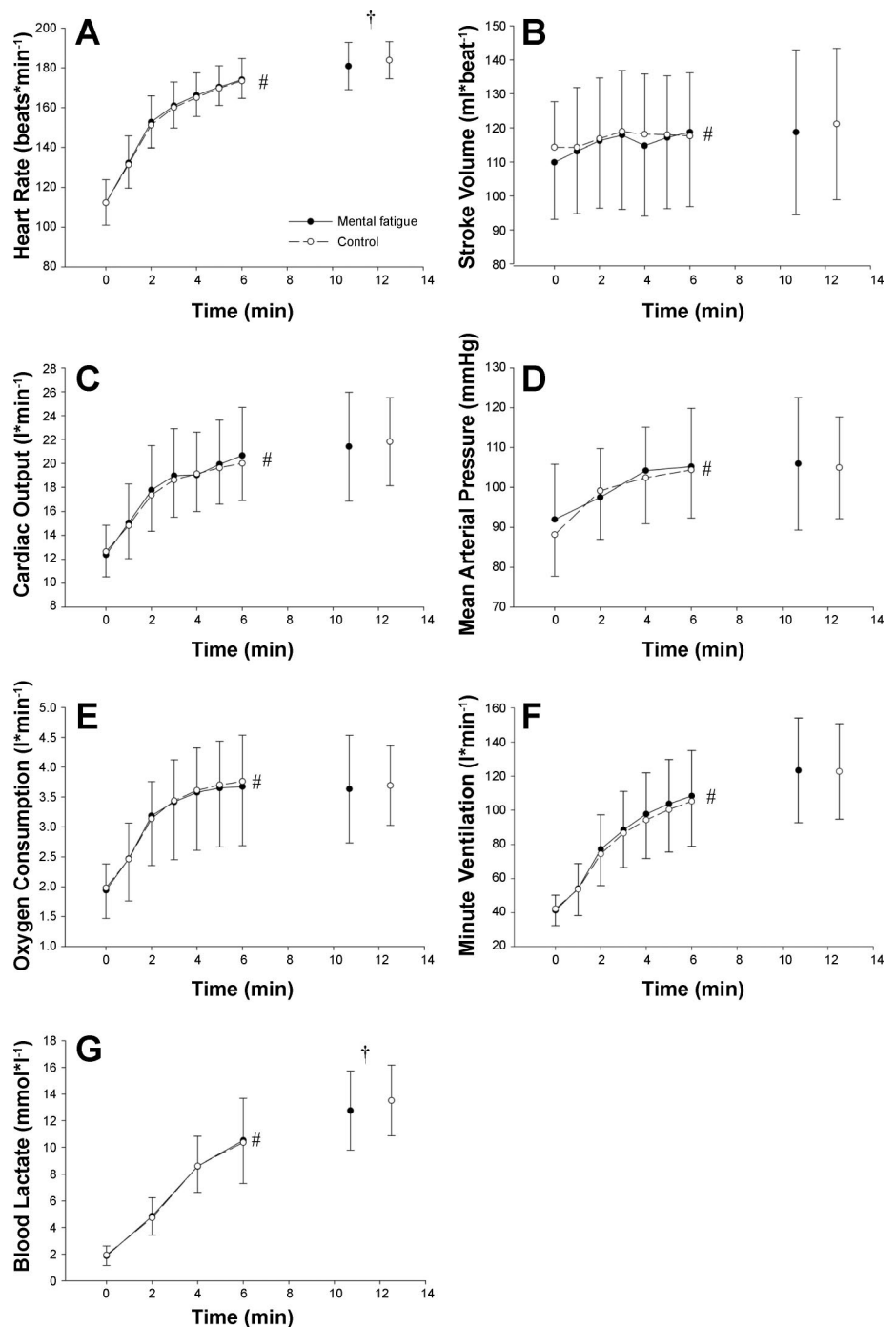


Fig. 2. Effects of mental fatigue on physiological responses during high-intensity cycling exercise. A: heart rate. B: stroke volume. C: cardiac output. D: mean arterial pressure. E: oxygen consumption. F: minute ventilation. G: blood lactate. # Significant main effect of time ($P < 0.05$). †Significant difference between mental and control condition at exhaustion ($P < 0.05$). Data are presented as means \pm SD. Minute 0 represents end of warm-up.

Effects of Mental Fatigue on Motivation and Perception of Effort During Exercise

Success motivation (mental fatigue 14.8 ± 4.7 , control 15.2 ± 5.2 , $P = 0.524$) and intrinsic motivation (mental fatigue 18.2 ± 4.5 , control 19.5 ± 4.1 , $P = 0.126$) did not differ significantly between conditions. RPEs at isotime increased similarly in both conditions (main effect of time, $P < 0.001$), but RPE was significantly higher in the mental fatigue condition compared with control (main effect of condition, $P = 0.007$) (Fig. 3). RPEs at exhaustion were not significantly different between conditions.

DISCUSSION

Markers of Mental Fatigue

The higher average HR during the AX-CPT compared with watching emotionally neutral documentaries confirms the demanding nature of this cognitive task (56). Indeed, during typical computer tasks like the AX-CPT (keystrokes at intervals of 300 ms or longer), physiological changes reflect mental effort rather than motor demands (34). However, contrary to previous suggestions (19), blood glucose levels were not sensitive to cognitive effort. As expected from earlier research (68), 90 min of this cognitively demanding task was effective in inducing a state of mental fatigue, which was demonstrated by an increase in subjective feelings of "tiredness" and "lack of energy," and a significant reduction in cognitive performance.

Effects of Mental Fatigue on Time to Exhaustion and Physiological Responses During High-Intensity Cycling Exercise

The main finding of our experimental study is that mental fatigue impairs physical performance, which was measured as time to exhaustion during high-intensity cycling exercise. This type of physical performance (short-term endurance in thermo-neutral conditions) is traditionally thought to be limited by cardiorespiratory and muscle-energetic factors (6, 11, 21, 31, 52, 71). Therefore, we tested the hypothesis that prior mental activity involving the ACC increases cardiovascular strain during exercise, thus leading to a premature plateau or drop in

cardiac output, altered muscle metabolism, and reduced performance (23, 24, 48, 49). This hypothesis is based on previous studies showing exaggerated cardiovascular responses during cognitive tasks in mentally fatigued subjects (75, 77) and evidence that the human cingulate cortex plays an important role in autonomic control during effortful cognitive and motor tests (16). However, we did not find any significant effect of mental fatigue on cardiovascular responses during high-intensity cycling with the exception of HR at exhaustion, which was significantly higher in the control condition, most likely because of longer exercise duration (15). The fact that mental fatigue did not exacerbate cardiovascular strain is probably due to the already high autonomic activation caused by central motor command (72) and the exercise pressor reflex during intense cycling (62). In such conditions, the influence of mental fatigue on cardiovascular responses may not be as significant as during cognitive tasks with relatively low autonomic activation (75, 77).

Given the lack of effect on cardiac output, it is not surprising that mental fatigue did not affect $\dot{V}O_2$, minute ventilation, and blood lactate responses with the exception of blood lactate concentration at exhaustion, which was actually higher in the control condition because of longer exercise duration (32). These findings suggest that mental fatigue does not affect oxygen kinetics, $\dot{V}O_{2peak}$, cycling economy, and the anaerobic threshold. It is also very unlikely that prior cognitive activity involving keystrokes with the middle or index finger causes fatigue in the locomotor and respiratory muscles, or depletion of anaerobic capacity. Therefore, the cardiorespiratory and muscle-energetic factors traditionally thought to determine short-term endurance performance (6, 11, 31, 71) could have not mediated the negative effect of mental fatigue on time to exhaustion during high-intensity cycling exercise. Similarly, lack of physiological alterations in the systems we investigated suggest that afferent feedback from peripheral organs to the brain is unlikely to have caused an increase in subconscious intelligent (63) or reflexlike (1) inhibition of central neural drive to the locomotor muscles in the mental fatigue condition.

Effects of Mental Fatigue on Motivation and Perceived Exertion

Our findings are consistent with the psychobiological model of exercise performance based on motivational intensity theory (42, 44). This effort-based decision-making model of endurance performance postulates that a time-to-exhaustion test is a motivated behavior ultimately determined by two cognitive and motivational factors: perceived exertion and potential motivation, i.e., the maximum effort an individual is willing to exert to satisfy a motive (76). Although aversion to further effort is a common feature of mental fatigue (8, 41, 67), we did not measure any significant effect of prior cognitive activity on either success or intrinsic motivation related to the time-to-exhaustion test. A possible explanation is that we artificially increased motivation of mentally fatigued subjects by offering monetary reward for best cycling performance (8). However, there is also evidence suggesting that the effect of fatigue on motivation is task specific. Indeed, Barth et al. (5) found that physical fatigue reduces the willingness to exert effort in subsequent physical tasks but not in subsequent mental tasks. Motivation related to these tasks is affected only by prior

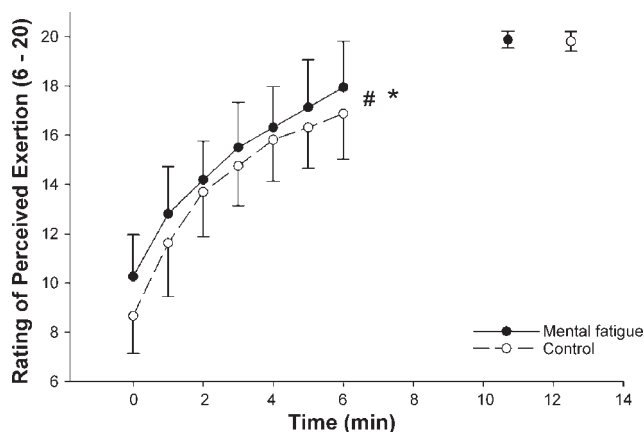


Fig. 3. Effect of mental fatigue on perception of effort during high-intensity cycling exercise. # Significant main effect of time ($P < 0.05$). *Significant main effect of condition ($P < 0.05$). Data are presented as means \pm SD. Minute 0 represents end of warm-up.

cognitive activity. Our finding that mental fatigue does not affect the willingness to exert effort during the subsequent physical task is in line with these observations.

Given no effect of mental fatigue on potential motivation in our experiment, the key to understand its negative effect on short-term endurance performance is the higher perception of effort measured during high-intensity cycling exercise (see Fig. 3, main effect of treatment on RPE at isotime). As RPE increased similarly over time in both conditions, mentally fatigued subjects reached their maximal level of perceived exertion and disengaged from the physical task earlier than in the control condition (see Fig. 3, RPE at exhaustion). These findings fit with Brehm's theory of motivation, which postulates that subjects decide to withdraw effort (i.e., disengage) when a task is perceived to be either too difficult or effort demands exceed the upper limit of what people are willing to do (76). Our results extend previous psychophysiological studies showing that mental fatigue increases effort responses to a performance challenge and lowers the level of task difficulty at which subjects decide to withhold effort (75, 77). Our results also agree with studies in which brain function was manipulated experimentally by other means. For example, Sgherza et al. (60) found that naloxone [an opioid antagonist that interferes with dopamine (29), a neurotransmitter involved in effort-based decision making (58)] increases RPE and reduces exercise time during an incremental cycling test despite similar physiological responses at the same workloads. Equally, 36 h of total sleep deprivation reduced time to exhaustion during intense treadmill walking by an average of 11% ($P = 0.05$) despite doubling monetary incentives for sleepless subjects (45). Again this negative effect was associated with higher RPE during exercise despite no major physiological alterations. Overall, it seems that exercise performance is ultimately limited by perception of effort rather than cardiorespiratory and musculoenergetic factors (60).

Potential Mechanisms for the Effect of Mental Fatigue on Perceived Exertion

Further research is necessary to understand why perceived exertion is higher in mentally fatigued subjects. A possible explanation is that mental fatigue affects central processing of the sensory inputs generating perception of effort during exercise (43). Preliminary evidence that prolonged and demanding cognitive activity disrupts sensorimotor gating (68) provides some support to this hypothesis. Another possible explanation is that mental fatigue directly affects the cortical centers involved in the cognitive aspects of central motor command (26), the primary sensory input for perceived exertion (43). A likely candidate is the ACC, a cortical area in which motor control, homeostatic drive, emotion, and cognition converge (54). This proposition is supported by several findings. First, this cortical area is strongly activated by tasks requiring significant cognitive effort (55) including the AX-CPT (4, 12), and it is known to be affected by mental fatigue (14, 39). Second, human neuroimaging studies have shown correlations between changes in ACC activity and changes in RPE during hypnotic manipulations of exercise intensity and motor imagery (72–74). Last, decision-making studies in rats with experimental ACC lesions demonstrate that they engage significantly less than normal rats in tasks requiring considerable

physical effort to obtain a larger reward (57, 69, 70). Such behavior is compatible with higher perceived exertion in these animals. Neuroimaging studies are needed to confirm our hypothesis that the ACC is involved in effort-related decision making in exercising humans and mediates the negative effect of mental fatigue on physical performance. Finally, higher perception of effort during exercise in mentally fatigued subjects may be related to altered brain energy metabolism and reduced glycogen levels (17, 20). However, in a recent study, the cerebral metabolic ratio has been experimentally dissociated from RPE during an incremental exercise test (37). More research is necessary to clarify the perceptual and functional consequences of the cerebral metabolic perturbations provoked by prolonged periods of exercise (53) and demanding cognitive activity (20).

Conclusions

Our study provides experimental evidence that mental fatigue limits exercise tolerance in humans through higher perception of effort rather than cardiorespiratory and musculoenergetic mechanisms. This finding has several important implications. First, it provides strong evidence that brain function can limit short-term endurance performance in thermoneutral conditions. This result is important because the hypothesis that the brain plays a significant role in regulating endurance performance is supported primarily by human studies during prolonged exercise in the heat (52), correlative electromyography data (1), theoretical considerations (33, 63), and animal studies (18, 47, 53). Second, the experimental procedures described here may provide a new paradigm for human studies into the neurocognitive aspects of fatigue and exercise performance, an important area of integrative physiology (27). Such studies may benefit not only endurance athletes, but also military personnel involved in physical work after prolonged periods of vigilance, and patients affected by unexplained chronic fatigue syndromes such as myalgic encephalomyelitis. Indeed, our experimental paradigm may serve as a human model of this condition, which is characterized by a similar picture of mental fatigue, increased perception of effort, and reduced performance during exercise despite no significant cardiorespiratory and musculoenergetic abnormalities (22). Finally, our findings provide further evidence of an interaction between physical and cognitive effort (40, 78). Future research in this area should investigate the common neurocognitive resources shared by these supposedly different activities, and the effects of mental fatigue on other types of physical performance.

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