Mental Fatigue Impairs Intermittent Running Performance

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ABSTRACT

SMITH, M. R., S. M. MARCORA, and A. J. COUTTS. Mental Fatigue Impairs Intermittent Running Performance. *Med. Sci. Sports Exerc.*, Vol. 47, No. 8, pp. 1682–1690, 2015. **Purpose**: The purpose of the study was to investigate the effects of mental fatigue on intermittent running performance. **Methods**: Ten male intermittent team sports players performed two identical self-paced, intermittent running protocols. The two trials were separated by 7 d and preceded, in a randomized-counterbalanced order, by 90 min of either emotionally neutral documentaries (control) or the AX-continuous performance test (AX-CPT; mental fatigue). Subjective ratings of fatigue and vigor were measured before and after these treatments, and motivation was recorded before the intermittent running protocol. Velocity, heart rate, oxygen consumption, blood glucose and lactate concentrations, and ratings of perceived exertion (RPE) were measured throughout the 45-min intermittent running protocol. Session RPE was recorded 30 min after the intermittent running protocol. **Results**: Subjective ratings of fatigue were higher after the AX-CPT ($P = 0.005$). This mental fatigue significantly reduced velocity at low intensities ($1.28 \pm 0.18\ m \cdot s^{-1}$ vs $1.31 \pm 0.17\ m \cdot s^{-1}$; $P = 0.037$), whereas high-intensity running and peak velocities were not significantly affected. Running velocity at all intensities significantly declined over time in both conditions ($P < 0.001$). Oxygen consumption was significantly lower in the mental fatigue condition ($P = 0.007$). Other physiological variables, vigor and motivation, were not significantly affected. Ratings of perceived exertion during the intermittent running protocol were not significantly different between conditions despite lower overall velocity in the mental fatigue condition. Session RPE was significantly higher in the mental fatigue condition ($P = 0.013$). **Conclusion**: Mental fatigue impairs intermittent running performance. This negative effect of mental fatigue seems to be mediated by higher perception of effort.

Key Words: COGNITIVE FATIGUE, TEAM SPORTS, PACING, PERCEIVED EXERTION

Mental fatigue is a psychobiological state operationally defined as an acute increase in subjective ratings of fatigue and/or an acute decline in cognitive performance; it is induced by prolonged periods of demanding cognitive activity (1,20). This acute fatigue associated with prolonged mental exertion is different from the chronic fatigue and cognitive impairment associated with aging or disease (e.g., cancer, chronic fatigue syndrome, and depression). In these conditions, subjective feelings of fatigue and cognitive impairment are chronic and not necessarily related to mental exertion (1,2). Only recently have studies begun to investigate the impact of mental fatigue on physical performance, revealing impairments to both constant-load (24,30) and self-paced (5,29) endurance exercise.

While these findings partly clarify the mechanisms and effects of mental fatigue on endurance performance, continuous exercise protocols (time to exhaustion tests and time trials) do not accurately reflect the demands of intermittent team sports. Indeed, intermittent team sports are stochastic in nature, requiring prolonged, intermittent high-intensity running. Therefore, the effects of mental fatigue on intermittent running performance may differ from those during time to exhaustion tests and time trials.

In team sports, a decline in both technical and physical performance is observed during a match (8,17,32,33). Time-motion analysis reveals transient reductions in distance covered after high-intensity periods of a match and a general reduction in distance covered throughout a match. Moreover, reductions in both qualitative and quantitative measures of technical ability have also been observed during a match (17,33). These reductions in technical and physical performance may be attributed to both neuromuscular fatigue (operationally defined as an exercise-induced reduction in maximal voluntary force or power) and mental fatigue (25). However, the extent to which mental fatigue contributes to the decline in both technical and physical performance observed during a match remains unclear. This may be due to the difficulties associated with investigating mental fatigue in a field setting.

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Indeed, studying the effects of mental fatigue during a match is impractical for two primary reasons. First, the potential for mental fatigue to influence match outcome prevents coaches from allowing such investigations. Second, the field-based environment does not provide the controlled conditions necessary for accurate assessment of the physiological and psychological mechanisms underlying the hypothesised negative effects of mental fatigue on technical and physical performance during a match. Therefore, studies must investigate the effects of mental fatigue on aspects of match performance in a controlled environment using protocols that closely reflect the demands of a match. Intermittent running protocols based on time-motion analysis data and performed on nonmotorized treadmills have been shown to be both valid and reliable for this purpose (34).

Therefore, the aims of this study were to i) examine the effect of experimentally induced mental fatigue on performance during a 45-min, self-paced, intermittent, high-intensity running protocol designed to simulate the activity profile of intermittent team sports, and ii) identify potential physiological and psychological mechanisms underpinning any change in performance. Based on the psychobiological model of endurance performance (21,23) and previous research (5,29), we hypothesized that mental fatigue would increase perception of effort, and, as a result, participants would choose to run at slower velocities during the intermittent running protocol.

METHODS

Participants

Ten male participants (mean age, 22 ± 2 yr; mean stature, 181 ± 4 cm; mean body mass, 75 ± 6 kg; $\dot{V}O_{2max}$: 48 ± 6 $mL \cdot kg^{-1} \cdot min^{-1}$) volunteered to participate in the investigation. All participants were current members of competitive intermittent sports teams (soccer, Australian football, rugby league, rugby union, or field hockey), had been playing competitively for at least 3 yr, and were free from any known illness or disease. The participants provided written informed consent, and the Human Research Ethics Committee of the University of Technology, Sydney approved the study procedures. All participants were provided with written instructions outlining the study's procedures but were not informed of its aims. Instead, to avoid nocebo effects on perception of effort and performance, the participants were told that the aim of the study was to compare the effects of two different cognitive activities on the physiological responses to intermittent running.

Experimental Overview

In this randomized, counterbalanced, crossover study, the participants visited the Human Performance Laboratory of the University of Technology, Sydney, on five separate occasions. The first three visits involved familiarization with all equipment and testing procedures as well as an incremental exercise test to determine $\dot{V}O_{2max}$. The final two visits involved performing either an experimental treatment to induce mental fatigue or a control treatment before a 45-min, self-paced, intermittent, high-intensity running protocol performed on a Force nonmotorized treadmill (Force Tread Dynameter; Woodway, Waukeshka, WI, USA).

During the familiarization visits, participants performed a 15-min intermittent running protocol on the nonmotorized treadmill. In accordance with previous suggestions (34), participants were familiarized with both running technique on the nonmotorized treadmill and target intensities (stand, 0%; walk, 20%; jog, 35%; run, 50%; fast run, 70%; and sprint, 100% of maximal effort) for the different activity zones of the intermittent running protocol. The participants were clearly informed that these intensities were to be used only as a guide, allowing for self-selected velocities during the intermittent running protocol. Instructions were also provided for the correct use of the CR100 RPE scales according to the methods of Borg and Borg (3). Blood and gas analyses were performed during familiarization to ensure participants were accustomed to all procedures. At the final familiarization visit, the participants were provided with instructions to sleep for at least 7 h, drink at least 35 mL $H_2O \cdot kg^{-1}$ body mass, refrain from consumption of alcohol, and avoid vigorous exercise the day before each of the following two visits (experimental and control trials). Instructions were also given to avoid caffeine and nicotine for 3 h before, and consume a light meal 2 h before testing.

Upon arrival for the experimental and control trials, the participants were asked to complete a pretest checklist, ensuring compliance with the provided instructions, as well as a mood questionnaire. After the questionnaire, a 0.6-μL sample of whole fresh blood was taken from a hyperemic fingertip to assess whether blood glucose concentration was within homeostatic levels. The participants then walked to an adjacent, quiet, dimly lit room, where the experimental or control treatment was administered. Throughout treatment, heart rate (HR) was measured every 5 s using Polar Team System RS800sd HR monitors (Polar, OY, Finland). After treatment, the participants returned to the laboratory, where they filled in the mood questionnaire for a second time as well as another questionnaire on motivation related to the upcoming intermittent running protocol. Another 0.6-μL blood sample was taken to assess blood glucose concentration as well as a 5-μL sample for assessment of blood lactate concentration ($[BLa^-]$). The second blood glucose concentration measurement was performed to assess whether experimental treatment depleted blood glucose more than control treatment. Previous research demonstrates that analysis of fingertip blood samples can detect differences in blood glucose depletion between demanding and easy cognitive tasks (14).

The participants then performed a standardized 5-min warm-up on the nonmotorized treadmill followed by 5 min of dynamic stretches in preparation for the upcoming intermittent running protocol. Blood samples were again collected to ensure baseline measures of $[BLa^-]$ and blood glucose

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concentration for the assessment of changes induced by the subsequent intermittent running protocol.

Intermittent Running Protocol

The self-paced, intermittent, high-intensity running protocol was designed to meet the specific needs of the current investigation. To reflect the running demands of various team sports, a protocol based on time-motion analysis data from multiple sports was required. Furthermore, it was necessary for this intermittent running protocol to be self-paced and allow for the comparison of short periods of identical activity to accurately monitor pacing profiles. Finally, the intermittent running protocol had to allow for regular measurement of various physiological and psychological parameters. Whereas previous investigations have found similar intermittent running protocols to be both valid and reliable, the existing protocols did not meet all of the aforementioned requirements, necessitating the development of the current intermittent running protocol (34).

Time motion analysis data from soccer, Australian football, rugby league, rugby union, and field hockey were used in the design of the intermittent running protocol (8,10,32,35,36). The protocol consisted of a standard 3-min block of activity (Fig. 1), which was repeated 15 times without rest for a total of 45 min. This allowed for consistency in data analysis and the ability to accurately monitor pacing profiles. The six different activities (stand, walk, jog, run, fast run, and sprint) were arranged in a pseudorandom order to simulate the stochastic nature of intermittent team sports. To avoid experimenter bias, no verbal encouragement was provided throughout the intermittent running protocol.

Treatment

Experimental treatment. Mental fatigue was induced experimentally using a prolonged version (90 min) of the AX-continuous performance test (AX-CPT). This demanding cognitive task requires vigilance, working memory, and response inhibition; and it has been successfully used to induce a state of mental fatigue in previous exercise studies (5,24,30). In short, the AX-CPT involves pressing one of two buttons in response to a string of letters displayed on a computer screen. AX-CPT performance is scored automatically on the basis of reaction time and accuracy of responses. Any missed or incorrect responses elicited a beep sound from two speakers as a prompt to increase speed and accuracy. As a reduction in working memory and vigilance are well established markers of mental fatigue (20), the number of correct responses in the first and last 15 min of the AX-CPT was compared as a manipulation check. A \$50 incentive was offered to the participant with the best scores to control for the negative effects of poor motivation and boredom on AX-CPT performance.

Control treatment. Control treatment consisted of watching 90 min of documentaries on the same computer screen used for the AX-CPT. The documentaries were "Railway Adventures Across Europe—Power To the Peaks; Trains, Mains and Automobiles; Silence of the Iron Horse and Tracks of Moors" (Payless Entertainment Pty. Ltd). These documentaries were chosen based on their similarity to those used in previous research (24), during which the participants maintained a neutral mood and stable HR. During both treatments, a member of the research team sat behind the participant to ensure compliance.

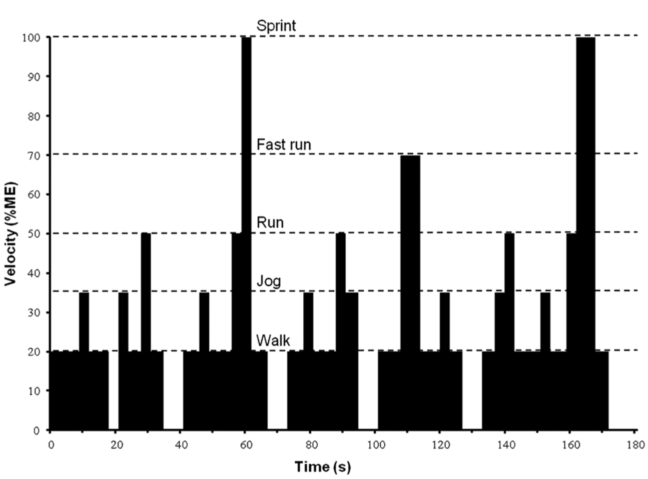

FIGURE 1—Standard 3-min block of intermittent running. %ME, percentage of maximal effort.

Measures

Intermittent running performance. During the intermittent running protocol, belt speed of the nonmotorized treadmill was monitored using two optical speed photomicrosensors (Model number EE-SX670, Omron Electronics, Schaumburg, IL) mounted on the rear roller shaft of the nonmotorized treadmill belt. Distance, velocity, and work data were recorded at a sampling rate of 10 Hz via the XPV7 PCB interface (Fitness Technology, Adelaide, Australia) and analyzed using the Force 3.0 software (Innervations Software, Joondalup, Australia). Performance data were categorized as either low-intensity activity (LIA) or high-intensity activity (HIA) for analysis. Low-intensity activity included all walking, jogging, and running (up to 50% of maximal effort), and HIA included only fast running and sprinting (70%–100% of maximal effort). The maximum single measure of velocity achieved during each 3-min block of activity was also recorded, and analyzed as "peak velocity." Previous research has shown this nonmotorized treadmill to be reliable for measuring performance data during intermittent running protocols similar to the present study (34).

Physiological responses to intermittent running. Oxygen consumption ($\dot{V}O_2$; $mL{\cdot}kg^{-1}{\cdot}min^{-1}$) was measured breath-by-breath during the intermittent running protocol using a computerized metabolic gas analysis system connected to a mouthpiece (Physiodyne, Quogue, NY, USA). This automated system was calibrated before each test using certified gases of known concentration (21.0% O_2 and 5.1%

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CO_2) and a 3-L calibration syringe for measures of volume and flow (Hans Rudolph, Inc, Kansas City, MO, USA).

Throughout the self-paced, intermittent, high-intensity running protocol, HR (bpm) was measured beat-by-beat and averaged every 5 s by Polar Team System RS800sd HR monitors (Polar, OY, Finland). The watch was worn on the wrist of the participant, with the display covered to blind participants from any HR or time feedback.

Blood samples were collected after warm-up and every 9 min during and 1 min after the intermittent running protocol; two blood samples were collected to assess blood glucose concentration and [BLa^-] ($mmol \cdot L^{-1}$). The first sample (5 μL) was analyzed for lactate using an Accusport portable lactate analyzer (Boehringer Mannheim, Germany). The second sample (0.6 μL) was analyzed for glucose using an Accu-Check Performa portable analyzer (Roche, USA). All blood samples were taken from the hyperemic fingertip of the left index finger.

Psychological measures. Ratings of perceived exertion were assessed every 5 min during the protocol using CR100 scales (3). A CR100 scale was displayed at eye level on the wall approximately 1.5 m in front of the participants at all times throughout the intermittent running protocol. Another CR100 scale was held in front of the participants every 5 min on which they pointed to a number to indicate their rating. One final RPE was recorded 30 min after the intermittent running protocol as a measure of session-RPE (15).

Mood was assessed before and after treatment using the Brunel Mood Scale (BRUMS) developed by Terry et al. (37). This questionnaire contains 24 items (e.g., annoyed, confused, depressed, exhausted, anxious, and active) divided into six respective subscales: anger, confusion, depression, fatigue, tension, and vigor. A five-point Likert scale (0, not at all; 1, a little; 2, moderately; 3, quite a bit; and 4, extremely) was used to respond to each item, resulting in a raw score of 0–16 for each subscale (four items per scale). For the purpose of this study, we report the fatigue and vigor subscales. An increase in subjective ratings of fatigue and/or a reduction in subjective ratings of vigor are well-established markers of fatigue in athletes (6).

Motivation related to the intermittent running protocol was measured using the intrinsic and success motivation scales developed and validated by Matthews et al. (26). Both scales contain seven statements (e.g., "I expect the content of the task will be interesting" and "I want to succeed on the task") scored on a five-point Likert scale (0, not at all; 1, a little; 2, moderately; 3, quite a bit; and 4, extremely). Therefore, total scores for each motivation scale range from 0 to 28.

Statistical Analyses

All data are presented as mean ± SD unless otherwise stated. After testing for normality, data were analyzed using two-way (condition × time) repeated-measures ANOVA and paired sample *t*-tests where appropriate. When the sphericity assumption was violated, the Greenhouse–Geisser correction was used. Significance was set at 0.05 (two-tailed) for all analyses.

RESULTS

Manipulation checks. Average HR was significantly higher during the AX-CPT (68 ± 9 bpm) compared to the control treatment (62 ± 8 bpm) ($P = 0.002$), whereas blood glucose concentration was similar and remained steady in both treatments (5.0 ± 0.4 to 4.9 ± 0.5 $mmol \cdot L^{-1}$; main effect of time, $P = 0.918$; main effect of condition, $P = 0.785$). The BRUMS questionnaire revealed a significant decrease in subjective ratings of vigor (7.6 ± 2.7 to 3.3 ± 2.5) after both treatments ($P < 0.001$), with no significant difference between conditions ($P = 0.501$). However, subjective ratings of fatigue increased significantly only after the AX-CPT (condition–time interaction; $P = 0.001$; Fig. 2). Follow-up tests revealed no significant difference in subjective ratings of fatigue before treatment ($P = 0.367$); but after treatment, subjective ratings of fatigue were significantly higher in the mental fatigue condition compared with the control condition ($P = 0.005$). Finally, the number of incorrect responses during the final 15 min of the AX-CPT (5.2 ± 3.1) was significantly higher compared to the first 15 min (2.4 ± 0.9; $P = 0.018$).

Intermittent running performance. Figure 3 displays the effects of mental fatigue on intermittent running performance. No significant condition–time interactions were observed for intermittent running performance at any velocity (overall, $P = 0.533$; LIA, $P = 0.600$; HIA, $P = 0.470$; and peak, $P = 0.437$). In both conditions, all velocities decreased significantly over time ($P < 0.001$).

Overall velocity and LIA velocity were significantly lower in the mental fatigue condition (overall, 1.50 ± 0.18 $m \cdot s^{-1}$; LIA, 1.28 ± 0.18 $m \cdot s^{-1}$) compared with the control condition (overall: 1.54 ± 0.18 $m \cdot s^{-1}$, $P = 0.022$; LIA: 1.31 ± 0.17 $m \cdot s^{-1}$, $P = 0.038$). However, HIA velocity and peak velocity were not significantly different between conditions (HIA: mental fatigue, 4.00 ± 0.39 $m \cdot s^{-1}$; control, 4.01 ± 0.36 $m \cdot s^{-1}$; $P = 0.892$; peak: mental fatigue, 4.86 ±

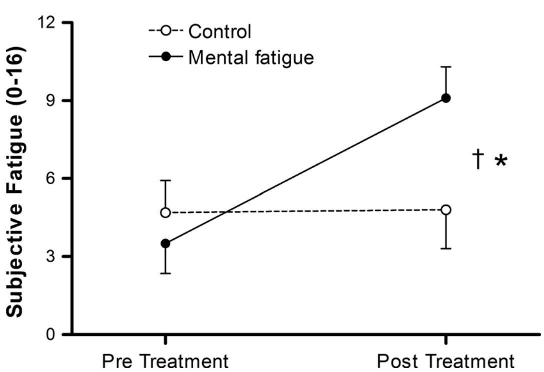

FIGURE 2—Effect of treatment on subjective ratings of fatigue. *Significant difference at post treatment ($P < 0.05$). †Significant condition–time interaction. Data are presented as mean ± SEM ($n = 10$).

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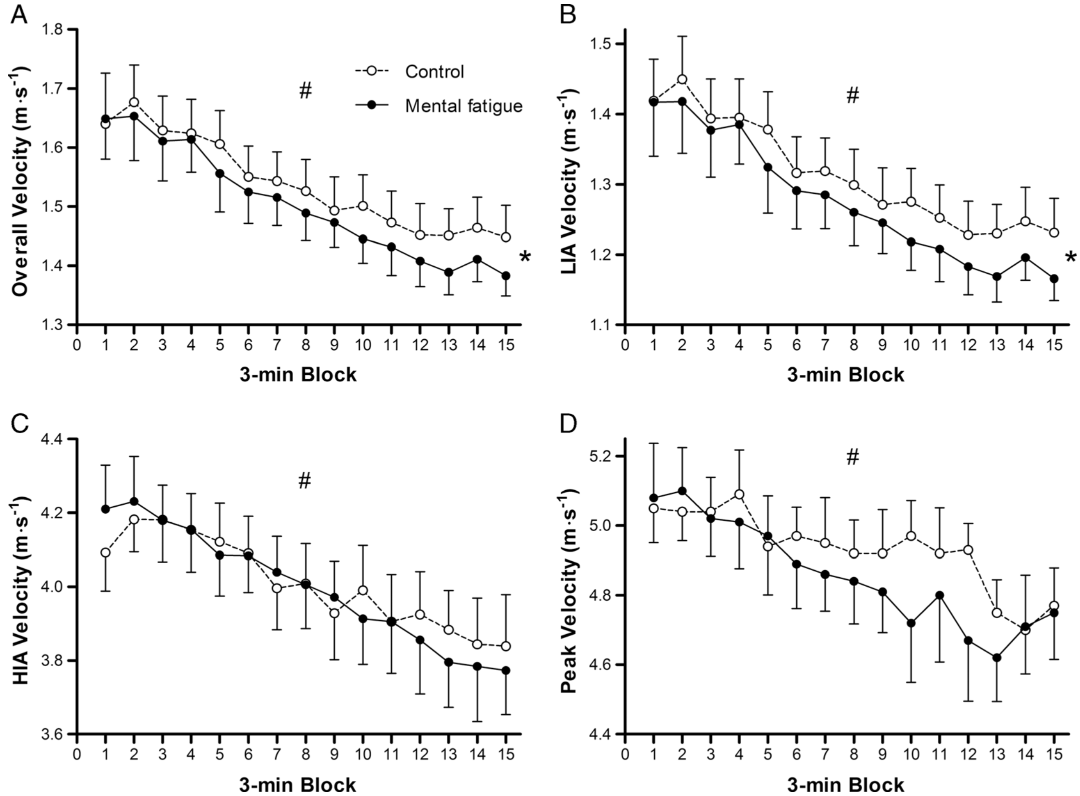

FIGURE 3—Effects of mental fatigue on intermittent running performance. A, Overall velocity. B, low-intensity activity (LIA) velocity. C, high-intensity activity (HIA) velocity. D, Peak velocity. *Significant main effect of condition (P < 0.05). #Significant main effect of time (P < 0.05). Data are presented as mean ± SEM (n = 10).

0.45 m·s^{-1}; control, 4.93 ± 0.35 m·s^{-1}; P = 0.652). Similarly, total distance and LIA distance were significantly lower in the mental fatigue condition (total distance, 4072 ± 409 m; LIA distance, 3164 ± 372 m) compared with the control condition (total distance: 4163 ± 430 m, P = 0.02; LIA distance, 3255 ± 366 m, P = 0.037), whereas HIA distance was not significantly different between conditions (mental fatigue, 908 ± 87 m; control, 908 ± 74 m; P = 0.982). In contrast, no significant differences existed between conditions for work performed at any intensity (total work: mental fatigue, 2294 ± 239 kJ; control, 2332 ± 259 kJ; P = 0.092; LIA work: mental fatigue, 1730 ± 211 kJ; control, 1771 ± 212 kJ; P = 0.100; HIA work: mental fatigue, 565 ± 65 kJ; control, 561 ± 55 kJ; P = 0.780).

Physiological measures. All physiological variables measured before, during, and/or after the intermittent running protocol (Table 1) showed significant main effects of time (all P < 0.001). However, no condition–time interactions were observed (all P > 0.05).

No significant differences were found between conditions for HR (P = 0.312), [BLa$^-$] (P = 0.809), or blood glucose concentration (P = 0.935). However, $\dot{V}O_2$ was

TABLE 1. Effects of mental fatigue on physiological responses to intermittent running.

	Pre	9 min	18 min	27 min	36 min	45 min
Blood glucose concentration, mmol·L^{-1}						
Control[a]	4.2 ± 0.6	4.7 ± 0.5	4.9 ± 0.6	5.2 ± 0.7	5.4 ± 0.7	5.3 ± 0.8
Mental fatigue[a]	4.3 ± 0.4	4.6 ± 0.5	5.2 ± 0.6	5.4 ± 0.9	5.1 ± 0.5	5.1 ± 0.5
Blood lactate concentration, mmol·L^{-1}						
Control[a]	3.5 ± 1.3	6.8 ± 4.0	6.1 ± 3.9	6.0 ± 4.0	5.7 ± 3.3	4.2 ± 3.2
Mental fatigue[a]	4.5 ± 2.0	7.8 ± 4.1	7.1 ± 3.6	5.5 ± 2.7	4.8 ± 2.9	3.7 ± 2.0
$\dot{V}O_2$,[b] mL·kg^{-1}·min^{-1}						
Control[a]		35.1 ± 4.5	37.1 ± 5.3	35.7 ± 4.5	34.2 ± 4.5	33.2 ± 4.2
Mental fatigue[a]		34.3 ± 6.1	36.0 ± 6.3	33.0 ± 5.1	31.2 ± 5.1	29.9 ± 5.1
Heart rate, bpm						
Control[a]		148 ± 16	159 ± 17	159 ± 17	160 ± 15	158 ± 15
Mental fatigue[a]		148 ± 21	158 ± 21	156 ± 19	156 ± 19	153 ± 19

Results are presented as mean ± SD.
[a]Significant main effect of time (P < 0.05).
[b]Significant main effect of condition (P < 0.05).

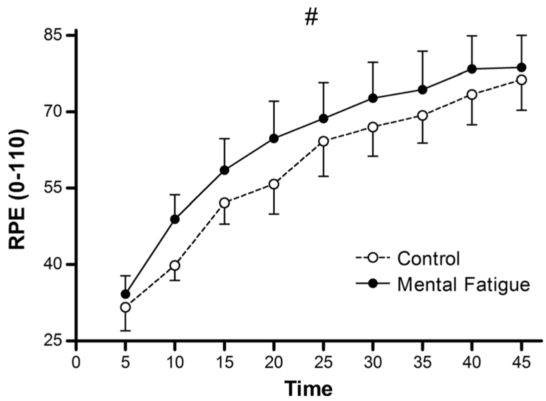

FIGURE 4—Effects of mental fatigue on RPE during intermittent running. #Significant main effect of time ($P < 0.05$). Data are presented as mean ± SEM ($n = 10$).

significantly lower in the mental fatigue condition (34.0 ± 4.9 $mL \cdot kg^{-1} \cdot min^{-1}$) compared to the control condition (36.0 ± 4.0 $mL \cdot kg^{-1} \cdot min^{-1}$; $P = 0.007$).

Psychological measures. The effects of mental fatigue on RPE during the intermittent running protocol are presented in Figure 4. Ratings of perceived exertion increased significantly over time in both conditions ($P < 0.001$); however, no significant main effect of condition (mental fatigue, 64.4 ± 23.9; control, 58.8 ± 21.8; $P = 0.137$) or condition–time interaction ($P = 0.729$) were observed. An area under the curve analysis performed on RPE data revealed no significant difference between conditions (mental fatigue, 2614 ± 750 RPE·min; control, 2378 ± 605 RPE·min; $P = 0.127$). Session RPE was significantly higher in the mental fatigue condition (70.0 ± 17.9) compared to the control condition (64.2 ± 16.2; $P = 0.013$).

Success motivation (mental fatigue, 16.7 ± 5.3; control, 17.2 ± 2.9; $P = 0.61$) and intrinsic motivation (mental fatigue, 7.8 ± 1.9; control, 7.0 ± 1.9; $P = 0.087$) related to the running protocol were not significantly different between conditions.

DISCUSSION

The aims of the present experimental study were to determine the effects of mental fatigue on intermittent running performance and to identify potential psychological and physiological mechanisms underpinning any change in performance. Results indicate that in agreement with our hypotheses, mental fatigue increases perception of effort and reduces overall velocity/LIA velocity during the intermittent running protocol. Apart from the significant reduction in $\dot{V}O_2$ associated with slower running velocity, no significant effects of mental fatigue were found on the physiological variables measured in the present study.

Experimentally induced mental fatigue. The AX-CPT, requiring vigilance, working memory, and response inhibition, has previously been identified as mentally fatiguing and was therefore used in the current investigation to induce mental fatigue (5,24,30). As expected, the AX-CPT successfully induced mental fatigue, as demonstrated by an increase in subjective ratings of fatigue and a reduction in cognitive performance over time. Furthermore, the mean HR during the AX-CPT was significantly higher than during the control condition, supporting previous investigations and further confirming the demanding nature of this cognitive task (24,30). Kohlisch and Schaefer (18) suggest that for computer tasks such as the AX-CPT, where keystrokes occur at intervals greater than 300 ms, physiological changes such as increased HR can be attributed to mental effort rather than physical effort. Upon arrival to the laboratory, blood glucose concentrations were similar between conditions and within normal homeostatic ranges. Despite previous suggestions that demanding cognitive tasks deplete more blood glucose than easy cognitive tasks (14), posttreatment blood glucose concentration was not different between the AX-CPT and watching documentaries. This finding is in agreement with previous research using the AX-CPT to induce mental fatigue (24,30) and recent criticism of the energy depletion model of self-regulation (19).

Effects of mental fatigue on intermittent running performance. In agreement with the primary hypothesis, mental fatigue caused a reduction in overall velocity during the intermittent running protocol. This decrease in overall velocity was a result of a reduced velocity during LIA, which comprised 91.7% of the protocol. The observed reduction in LIA velocity corresponded to a 91-m reduction (2.8%) in distance traveled during LIA zones. Notably, mental fatigue did not affect velocity or the corresponding distance traveled during HIA zones or peak velocities. These findings suggest that when mentally fatigued, players may regulate their pace at low intensities, maintaining the ability to perform during high-intensity efforts. In the field, this pacing profile may be a strategic decision owing to the potential for high-intensity efforts to have a greater influence on match outcome and may explain why some investigations have reported the maintenance of very high intensity and peak velocities in the final stages of a match (8,11).

Alternatively, mental fatigue may not impair performance during high-intensity efforts lasting only a few seconds. Indeed, this was the case in a recent investigation into the effects of mental fatigue on neuromuscular function that showed no significant effect of mental fatigue on MVC (30). In that study, after 90 min of AX-CPT, participants performed two 5-s MVC of the knee extensors, separated by submaximal (20% MVC) knee extensor exercise to exhaustion. Results revealed that time to exhaustion (a measure of endurance performance) was 13% shorter in the mental fatigue condition compared to the control condition. However, MVC torque was not significantly affected by mental fatigue. The MVC torque declined in both conditions only after submaximal knee extensor exercise, indicating significant neuromuscular fatigue.

In support of these previous findings, the present results showed that mental fatigue significantly reduced LIA velocity (endurance performance), whereas performance during high-intensity efforts lasting only a few seconds (HIA and peak velocities) was unaffected. Furthermore, HIA and peak velocities decreased over time in both conditions similar to the decline in MVC torque observed by Pageaux et al. (30) after submaximal knee extensor exercise. Together, these results suggest that unlike endurance performance, high-intensity efforts lasting a few seconds are primarily affected by neuromuscular fatigue, with minimal influence from mental fatigue. One potential explanation for this finding is that mental fatigue has a limited effect on the main physiological factors determining performance during high-intensity efforts lasting only a few seconds, i.e., the contractile properties of the active muscles and the capacity of the CNS to recruit them (30). From a psychological perspective, it is possible that knowing an exercise bout lasts only a few seconds may increase self-efficacy and offset the negative effect of mental fatigue on perception of effort (23,27). Alternatively, during short bouts of HIA, participants may not perceive a difference in the effort required to perform, but may be more consciously aware of this difference during LIA and thus reduce speed to maintain an appropriate perception of effort (13).

Effects of mental fatigue on physiological responses to intermittent running. The HR and $[BLa^-]$ values recorded in the current investigation align with those previously observed during intermittent team sport matches (9,12), indicating that our intermittent running protocol performed on a nonmotorized treadmill accurately simulated the physical demands of match play in most team sports. However, no significant differences in HR or $[BLa^-]$ were found between conditions. The only physiological response to intermittent running that was significantly different between conditions was $\dot{V}O_2$, which was lower in the mental fatigue condition compared to the control condition. This difference was most likely due to lower LIA velocity chosen by the subjects rather than a direct metabolic effect of mental fatigue. Therefore, the negative effects of mental fatigue on intermittent running performance cannot be explained by impaired cardiovascular or metabolic responses as shown by previous exercise studies on the cardiovascular and metabolic effects of mental fatigue (24).

It has been previously suggested that demanding cognitive tasks similar to the AX-CPT can impair performance in subsequent cognitive or physical tasks by depleting blood glucose (14). This argument is based on the hypothesis that blood glucose is the energy substrate for self-regulation (16). There is also evidence that glucose availability can have an effect on intermittent high-intensity running performance (31). However in the present investigation, the AX-CPT did not deplete blood glucose before the intermittent running protocol. Furthermore, blood glucose concentration was not significantly different between conditions during the intermittent running protocol and increased over time, suggesting that adequate blood glucose was available to sustain performance.

Psychological effects of mental fatigue. The psychobiological model of endurance performance based on motivational intensity theory (4) has previously been shown to provide a valid explanation for the negative effects of mental fatigue on performance during constant-load (24,30) and self-paced endurance exercise (5,29). The psychobiological model postulates that endurance performance is a consciously regulated behavior primarily determined by two psychological factors: perception of effort and potential motivation. As in previous investigations, success motivation and intrinsic motivation were not reduced by mental fatigue (5,24). Therefore, the most likely explanation for the observed impairment in intermittent running performance in the mental fatigue condition is a higher perception of effort. Because RPE is a psychophysical measure (3), it is important to consider both the physical stimulus (workload) and the perceptual response (RPE) when drawing conclusions about perception of effort during exercise. Although RPE during the intermittent running protocol was not significantly different between conditions in our study, it tended to be higher in the mental fatigue condition despite significantly lower LIA velocity (i.e., lower workload). This finding is equivalent to significantly higher RPE for the same running velocity and indicates that perception of effort was higher in the mental fatigue condition. Furthermore, session-RPE was significantly higher in the mental fatigue condition. Importantly, the abnormally high perception of effort we observed in mentally fatigued players during intermittent running is consistent with previous studies using both constant-load (24,30) and self-paced (5,29) endurance exercise.

As recently discussed by Pageaux et al. (29), Edwards and Polman (13) and Brownsberger et al. (5), the choice to exercise at a lower workload in conditions of mental fatigue can be considered a behavioral response to maintain normal RPE and complete the task despite higher perception of effort. Although this behavioral response is consistent with the psychobiological model of endurance performance (21,23), the central governor model and its slight variations (28,38,39) also include perception of effort in the regulation of self-paced endurance exercise, and they have been applied to intermittent team sports (40). However, we consider these theoretical models to be biologically implausible, unnecessarily complex, and internally incoherent (21). The common observation that humans with a normal CNS can exercise beyond the onset of myocardial ischemia also refutes their basic assumption that the CNS regulates muscle recruitment and/or generates RPE to prevent harm during exercise (22).

Limitations and directions for future research. Although the results of this experimental investigation clearly demonstrate the negative influence of mental fatigue on intermittent running performance, some limitations exist. Whereas the intermittent running protocol used in the current investigation was designed to simulate the activity profile of intermittent team sports and elicited similar HR and $[BLa^-]$ responses, a laboratory-based investigation cannot entirely replicate an intermittent team sport match. Therefore, it is difficult to determine whether the observed changes in overall velocity and LIA velocity would translate into meaningful differences in running performance during a real match. Additionally, whereas running profiles partly determine intermittent team sports performance, factors such as skill execution and decision making also affect match outcome and should be examined in future research. Indeed, the combined negative effects of mental fatigue on physical, technical, and tactical performance may have an additive or synergic impact on intermittent team sport performance.

Future research should also investigate the effects of mental fatigue on intermittent team sport performance using experimental treatments more akin to the cognitive tasks players may perform before matches. Examples include playing video games, attending tactical briefings, emotion regulation (e.g., controlling anger toward journalists during interviews or controlling anxiety before a match), and rumination. Because specific video footage and coach feedback can influence outcome during intermittent team sport matches (7), the choice of control treatments should also be carefully considered. In the present study, the participants of the documentaries watched as control treatments were emotionally neutral and totally unrelated to intermittent running performance. If anything, the decline in subjective vigor associated with watching these documentaries may have had a negative effect on intermittent running performance, thus leading to an underestimation of the negative effect of mental fatigue. Future studies may consider different control treatments or the inclusion of a condition with no treatment at all. Finally, although the observed differences in performance in the current investigation cannot be explained by the measured cardiovascular and metabolic variables, recent research has reported changes in hormonal state after cognitive prematch activity (7). Therefore, future research may benefit from the measurement of other physiological variables such as free testosterone and cortisol, as they may indirectly influence performance outcomes. Neurophysiological investigations aimed at understanding the brain alterations underlying the negative effect of mental fatigue on perception of effort are also warranted.

Conclusions and practical applications. In summary, this experimental investigation shows that prolonged and demanding cognitive activity leading to mental fatigue impairs performance during a subsequent self-paced, intermittent, high-intensity running protocol lasting 45 min. Specifically, when mentally fatigued, participants reduced LIA velocity but maintained HIA and peak velocities. Furthermore, the observed reduction in LIA velocity is most likely mediated by an increased perception of effort in mentally fatigued participants rather than cardiovascular or metabolic mechanisms. The intermittent running protocol used in this investigation was based on time-motion analysis data from intermittent team sports, and the physiological responses confirm that the protocol did indeed simulate the physical demands of a match. Therefore, mental fatigue may induce similar reductions in performance during intermittent team sport matches. Based on our findings, we suggest that common prematch activities be assessed, ensuring that intermittent team sport players avoid cognitively demanding activity before matches. Furthermore, coaches may benefit from measuring mental fatigue before matches and implementing strategies to combat mental fatigue.

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