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ORIGINAL ARTICLE

Response inhibition impairs subsequent self-paced endurance performance

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Abstract

Purpose The aim of this study was to test the effects of mental exertion involving response inhibition on pacing and endurance performance during a subsequent 5-km running time trial.

Methods After familiarization, 12 physically active subjects performed the time trial on a treadmill after two different cognitive tasks: (i) an incongruent Stroop task involving response inhibition (inhibition task) and (ii) a congruent Stroop task not involving response inhibition (control task). Both cognitive tasks were performed for 30 min.

Results Neither the inhibition nor the control task induced subjective feelings of mental fatigue. Nevertheless, time trial performance was impaired following the inhibition task (24.4 ± 4.9 min) compared to the control task (23.1 ± 3.8 min) because of a significant reduction in average running speed chosen by the subject. The response inhibition task did not affect pacing strategy, which was negative in both conditions. Heart rate and blood lactate responses to the time trial were not affected by the inhibition task, but subjects rated perceived exertion higher compared to the control condition (13.5 ± 1.3 vs 12.4 ± 1.3).

Conclusion These findings show for the first time that 30 min of mental exertion involving response inhibition reduces subsequent self-paced endurance performance despite no overt mental fatigue. The impairment in endurance performance observed after the incongruent Stroop task seems to be mediated by the higher perception of effort as predicted by the psychobiological model of endurance performance.

Keywords Perception of effort · Time trial · Mental fatigue · Running · Cognitive task · Stroop task

Abbreviations

ACC	Anterior cingulate cortex
ANOVA	Analysis of variance
HR	Heart rate
RPE	Rating of perceived exertion

Introduction

Mental exertion refers to the engagement with a demanding cognitive task. When prolonged, it can induce a psychobiological state of mental fatigue characterized by subjective feelings of "tiredness" and "lack of energy" (Boksem and Tops 2008). Recent studies have demonstrated the negative impact of mental fatigue induced by prolonged mental exertion (90 min) on subsequent endurance performance during whole-body (Marcora et al. 2009) and single-joint exercise (Pageaux et al. 2013). These studies demonstrated a higher perception of effort independently of any alteration of the cardiorespiratory, metabolic and neuromuscular responses to exercise. These results support the psychobiological model of endurance performance in which perception of effort plays a major role in limiting endurance performance (Marcora and Staiano 2010).

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In these studies, the negative effects of prior mental exertion on endurance performance were demonstrated with time to exhaustion tests. These tests are sensitive to changes in endurance performance (Amann et al. 2008), but do not allow for the self-regulation of speed/power output during endurance exercise (pacing). Therefore, the effect of prior mental exertion on pacing is not known at present. Because pacing is involved in all competitive endurance events, it is important for coaches and athletes to know whether prior mental exertion can affect the pacing strategy, i.e. the self-selected strategy or tactic adopted by an athlete (Abbiss and Laursen 2008).

From a more basic perspective, it is important to understand the contribution of specific cognitive process to the reduction in endurance performance observed after mental exertion. Of particular interest is response inhibition. This cognitive process refers to the inhibition of inappropriate/unwanted motor or emotional responses (Mostofsky and Simmonds 2008) and it is a main component of decision-making in human volition (Haggard 2008). Cognitive tasks involving response inhibition are known to activate the pre-supplementary motor area and the anterior cingulate cortex (ACC) during Stroop tasks (Mostofsky and Simmonds 2008). Activity in these cortical areas has been linked with perception of effort (de Morree et al. 2012; Williamson et al. 2001, 2002), and damage to the ACC is known to affect effort-based decision-making in animals (Rudebeck et al. 2006; Walton et al. 2003, 2006). Therefore, it is biologically plausible that prior mental exertion involving response inhibition would affect the effort-based decision-making process thought to regulate self-paced endurance performance (Marcora 2010a).

The aim of our study was to investigate the effects of response inhibition on pacing, perception of effort and performance during subsequent self-paced endurance exercise. Specifically, we hypothesized that prior mental exertion involving response inhibition would increase perception of effort and impair endurance performance to a larger extent than prior mental exertion without response inhibition. To test these hypotheses, we compared an inhibition condition (incongruent Stroop task) with a cognitive task that does not involve response inhibition (congruent Stroop task; Bray et al. 2008; Stroop 1992). Because the negative effects of prior mental exertion on perception of effort and endurance performance are well known (Marcora et al. 2009; Pageaux et al. 2013), we did not include a pure control condition with no prior mental exertion. To investigate the effect of response inhibition on pacing, we measured endurance performance with a 5-km running time trial in which subjects were free to self-regulate their speed on the treadmill.

Methods

Subjects and ethical approval

Twelve adults (eight males and four females; mean ± standard deviation (SD); age: 21 ± 1 year, height: 174 ± 12 cm, weight: 69 ± 11 kg) volunteered to participate in this study. None of the subjects had any known mental or somatic disorder. All subjects were involved in aerobic activities for at least two times a week in the previous 6 months. This level of training corresponds to the performance level 2 in the classification of subject groups in sport science research (De Pauw et al. 2013). Each subject gave written informed consent prior to the study. The experimental protocol and procedures were approved by the Ethics Committee of the School of Sport and Exercise Sciences, University of Kent, UK. The study conformed to the standards set by the World Medical Association Declaration of Helsinki "Ethical Principles for Medical Research Involving Human Subjects" (2008) All subjects were given written instructions describing the experimental protocol and procedures, but were naive to its aims and hypotheses. To ensure high motivation during the cognitive tasks and the time trials, a reward (£10 Amazon voucher) was given to the best overall performance in all the cognitive tasks and time trials. At the end of the last session, subjects were debriefed and asked not to discuss the real aims of the study with other participants.

Experimental protocol

Subjects visited the laboratory on three different occasions. During the first visit, subjects were familiarized with the experimental procedures. During the second and third visit, subjects performed either a cognitive task involving the response inhibition process (inhibition condition) or a cognitive task that did not involve response inhibition (control condition, see "Cognitive tasks" for more details) in a randomized and counterbalanced order (randomized crossover design). After the cognitive task, subjects performed a 5-km running time trial on a treadmill (see "Time trial" for more details). An overview of the experimental protocol is provided in Fig. 1. Mood was assessed before and after the cognitive task, and subjective workload was assessed after the cognitive task and after the time trial, whilst motivation was only measured before the time trial. Heart rate (HR) was recorded continuously throughout the experiment. Capillary blood samples were taken before and after the cognitive task, and after the time trial. For more details see "Physiological measurements" and "Psychological measurements".

Each participant completed all three visits over a period of 2 weeks with a minimum of 48 h recovery period

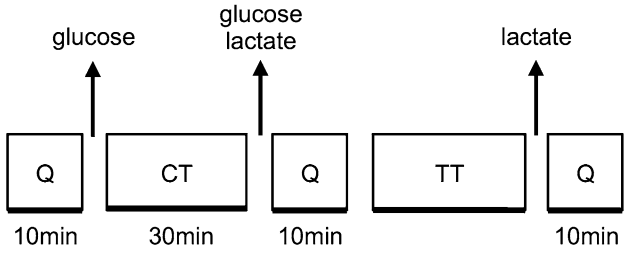

Fig. 1 Graphical overview of the experimental protocol. Order and timing were the same for each subject and each session. *CT* cognitive tasks, *Q* psychological questionnaires, *TT* 5-km running time trial

between visits. All participants were given instructions to sleep for at least 7 h, refrain from the consumption of alcohol and not to practice vigorous physical activity the day before each visit. Participants were also instructed to avoid caffeine and nicotine for at least 3 h before visiting the laboratory and were asked to declare if they had taken any medication or had any acute illness, injury or infection.

Cognitive tasks

Inhibition task

The inhibition condition consisted of 30 min of engagement with a modified incongruent version of the Stroop colour-word task. This 30-min task is known to reduce persistence in a figure-tracing task (Wallace and Baumeister 2002). Participants performed this inhibition task on a computer whilst sitting comfortably in a quiet and dim lit room. Four words (yellow, blue, green, red) were serially presented on the screen until the participant validated an answer and were followed by a 1,500 ms interval. Subjects were instructed to press one of four coloured buttons on the keyboard (yellow, blue, green, red) with the correct response being the button corresponding to the ink colour (either yellow, blue, green, red) of the word presented on the screen. For example, if the word blue appeared in yellow ink, the yellow button had to be pressed. If however the ink colour was red, the button to be pressed was the button linked to the real meaning of the word, not the ink colour (e.g. if the word blue appears in red, the button blue has to be pressed). If the ink colour was blue, green or yellow, then the button pressed matched the ink colour. The word presented and its ink colour were randomly selected by the computer (100 % incongruent). Twenty practice attempts were allowed before the inhibition task to ensure the participant understood the concept fully. The inhibition task was also performed for 5 min during the familiarization visit. Subjects were instructed to respond as quickly and accurately as possible. Visual feedback was given after each word in the form of correct or incorrect answer, response speed and accuracy. Participants were also informed that points would be awarded for speed and accuracy of their responses, and the score for both cognitive tasks would be added to the score for each time trial, to reward the overall highest score with a £10 Amazon voucher to increase motivation.

Control task

The control condition consisted of 30 min of engagement with a congruent version of the Stroop colour-word task. This control task was similar to the modified incongruent version of the Stroop colour-word task. However, the response inhibition process was not involved in this congruent version. Indeed, all words presented and their ink colour were matched (e.g. the word green was presented with a green ink colour).

Subjects were familiarized with all the procedures described above during the first visit to the laboratory. Cognitive performance during the congruent and incongruent Stroop colour-word tasks was measured in term of response accuracy (percentage of correct responses) and reaction time. Performance data were analysed off-line using the E-Prime software (Psychology Software Tools, Pittsburgh, PA, USA) and averaged in a non-cumulative way for each of six 5-min periods during both cognitive tasks.

Time trial

Ten minutes after completion of the allocated cognitive task, subjects performed a time trial on a treadmill to evaluate pacing and endurance performance. The treadmill (PowerJog, Expert Fitness UK Ltd, Glamorgan, Wales) was set at a 1 % gradient (Jones and Doust 1996). Subjects were asked to run 5 km in the quickest time possible. Each participant performed a standardized warm-up running on the treadmill at 8 km/h for 5 min. Feedback on the distance covered was available throughout the time trial. On the contrary, information about running speed, HR and time elapsed was not provided to the subject. The time trial started with subjects standing on the treadmill belt while running speed was increased up to 9 km/h. After this running speed was reached, subjects were free to choose their running speed using the + and − button on the right side of the treadmill. Throughout the time trial, participants were reminded at the end of each kilometre that they were able to increase or decrease their running speed at any time; however, the experimenters provided no encouragement during the time trial. Once the 5 km were completed, subjects stopped running immediately and placed their feet on the platform at the sides of the belt while time elapsed was recorded. The time elapsed was used as a measure of endurance performance. A fan was placed in a standardized position in front of the subject during the entire duration of the time trial and subjects were allowed to drink water. At the end of the first minute, and at the end of each kilometre, rating of perceived exertion (RPE), HR and running speed were recorded. To reduce the learning effect, subjects performed a familiarization time trial during the first visit to the laboratory.

Physiological measurements

Heart rate

HR was recorded continuously during both cognitive tasks and the time trial using an HR monitor (Polar RS400, Polar Electro Oy, Kempele, Finland) with an acquisition frequency of 1 sample/s. Data were analysed off-line and averaged for the whole duration of both cognitive tasks. During the time trial, HR values were collected the last 15 s of the warm-up, the first minute and for each kilometre completed.

Blood lactate and glucose concentrations

10 μl samples of capillary blood were taken from the thumb of the non-dominant hand of the subjects for measurement of blood lactate and blood glucose concentrations (Biosen, EFK Diagnostics, London, England). Blood glucose concentration was measured pre- and post-cognitive task, and blood lactate concentration was measured pre- and post-time trial.

Psychological measurements

Perception of effort

Perception of effort, defined as "the conscious sensation of how hard, heavy, and strenuous exercise is" (Marcora 2010b), was measured at the end of the first minute and at the end of each kilometre of the time trial using the 15 points RPE scale (Borg 1998). Standardized instructions for the scale were given to each subject before the warm-up. Briefly, subjects were asked to rate how hard they were driving their legs, how heavily they were breathing and the overall sensation of how strenuous exercise was. For example, nine corresponds to a "very light" exercise. For a normal, healthy person it is like walking slowly at his or her own pace for some minutes. Seventeen corresponds to a "very hard" and strenuous exercise. A healthy person can still go on, but he or she really has to push him or herself. It feels very heavy, and the person is very tired.

Mood

The Brunel Mood Scale developed by Terry et al. (2003) was used to quantify current mood ("How do you feel right now?") before and after the cognitive task. This questionnaire contains 24 items (e.g. "angry, uncertain, miserable, tired, nervous, energetic") divided into six subscales: Anger, Confusion, Depression, Fatigue, Tension and Vigour. The items are answered on a five-point 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 0–16. Only scores for the Fatigue and Vigour subscales were considered in this study as subjective markers of mental fatigue.

Motivation

Motivation related to the time trial was measured using the success motivation and intrinsic motivation scales developed and validated by Matthews et al. (2001). Each scale consists of seven 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 five-point 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.

Subjective workload

The National Aeronautics and Space Administration Task Load Index (NASA-TLX) rating scale (Hart and Staveland 1988) was used to assess subjective workload. The NASA-TLX is composed of six subscales: mental demand (How much mental and perceptual activity was required?), physical demand (How much physical activity was required?), temporal demand (How much time pressure did you feel due to the rate or pace at which the task occurred?), performance (How much successful do you think you were in accomplishing the goals of the task set by the experimenter?), effort (How hard did you have to work to accomplish your level of performance?) and frustration (How much irritating or annoying did you perceive the task?). The participants had to score each of the items on a scale divided into 20 equal intervals anchored by a bipolar descriptor (e.g. high/low). This score was multiplied by 5, resulting in a final score between 0 and 100 for each of the subscales. Participants completed the NASA-TLX after the cognitive task and after the time trial. All participants were familiarized with all psychological measurements during their first visit to the laboratory.

Statistics

All data are presented as mean ± SD unless stated. Assumptions of statistical tests such as normal distribution and sphericity of data were checked as appropriate.

Greenhouse–Geisser correction to the degrees of freedom was applied when violations to sphericity were present. Paired *t* tests were used to assess the effect of condition (inhibition vs control) on endurance performance, motivation scores, NASA-TLX scores after the cognitive tasks and after the time trial, HR during both cognitive tasks and HR during the warm-up before the time trial. Fully repeated measure 2 × 6 ANOVAs were used to test the effect of time (5-min blocks) and condition on response accuracy and reaction time during cognitive tasks. Fully repeated measure 2 × 2 ANOVAs were used to test the effect of condition and time on mood before and after the cognitive tasks, and the effect of condition and time on blood glucose and lactate concentrations. Fully repeated measure 2 × 6 ANOVAs were used to test the effect of condition and distance on HR, RPE and running speed during the time trial. Significant main effects of time with more than two levels and significant interactions were followed up with simple main effects of time or condition using Bonferroni correction as appropriate. The significance was set at 0.05 (two-tailed) for all analyses. Effect size for each statistical test was also calculated as partial eta squared (η_p^2). All analyses were conducted using the Statistical Package for the Social Sciences, version 19 for Mac OS X (SPSS Inc., Chicago, IL, USA).

Results

Effects of response inhibition on HR, blood glucose concentration and cognitive performance during the cognitive tasks

Heart rate (Fig. 2a) was significantly higher during the inhibition task compared to the control task ($P = 0.003$, $\eta_p^2 = 0.120$). Response inhibition did not affect ($F_{(1, 11)} = 0.059$; $P = 0.812$, $\eta_p^2 = 0.005$) the significant decrease in blood glucose concentration observed after the cognitive tasks ($F_{(1, 11)} = 7.209$; $P = 0.021$, $\eta_p^2 = 0.396$) (Fig. 2b).

Accuracy of responses during the cognitive tasks (Fig. 2c) was not affected by response inhibition ($F_{(1,11)} = 2.561$; $P = 0.138$, $\eta_p^2 = 0.189$) and did not change significantly over time ($F_{(2.214, 24.353)}$; $P = 0.058$, $\eta_p^2 = 0.221$). Similarly, reaction time (Fig. 2d) did not change significantly over time ($F_{(1.948, 21.425)} = 0.585$; $P = 0.562$, $\eta_p^2 = 0.050$), but it was significantly longer during the inhibition task compared to the control task ($F_{(1, 11)} = 68.474$; $P < 0.001$, $\eta_p^2 = 0.862$) (Fig. 2d).

Effects of response inhibition on mood and motivation

The mood questionnaire did not show any significant main effect of time ($F_{(1, 11)} = 1.194$; $P = 0.298$, $\eta_p^2 = 0.098$), condition ($F_{(1, 11)} = 0.021$; $P = 0.888$, $\eta_p^2 = 0.002$) or interaction ($F_{(1, 11)} = 0.096$; $P = 0.763$, $\eta_p^2 = 0.009$) in the Fatigue scores (Fig. 2e). The Vigour scores decreased over time (inhibition condition 5.9 ± 1.1–4.2 ± 1.0, control condition 6.1 ± 1.4–4.6 ± 1.5; $F_{(1, 11)} = 6.396$; $P = 0.028$, $\eta_p^2 = 0.368$) independently of the response inhibition process ($F_{(1, 11)} = 0.074$; $P = 0.791$, $\eta_p^2 = 0.057$).

There were no significant differences between conditions in intrinsic motivation (inhibition condition 18.5 ± 3.2, control condition 18.9 ± 4.5; $P = 0.622$, $\eta_p^2 = 0.023$) and success motivation (inhibition condition 17.5 ± 5.6, control condition 16.4 ± 6.0; $P = 0.151$, $\eta_p^2 = 1.78$) related to the subsequent time trial.

Effects of response inhibition on pacing and performance during the time trial

Time to perform the time trial was significantly longer following the inhibition task (24.4 ± 4.9 min) compared to the control task (23.1 ± 3.8 min; $P = 0.008$, $\eta_p^2 = 0.489$), with no significant learning effect ($P = 0.571$, $\eta_p^2 = 0.026$). Time trial performance decreased following the inhibition task in 10 out of 12 subjects.

Impaired time trial performance was caused by a significant reduction in running speed in the inhibition condition compared to the control condition ($F_{(1, 11)} = 14.117$; $P = 0.003$, $\eta_p^2 = 0.562$) (Fig. 3a). However, response inhibition did not affect pacing strategy as demonstrated by the lack of significant interaction between condition and distance ($F_{(1.724, 18.964)} = 0.832$; $P = 0.434$, $\eta_p^2 = 0.070$). In both conditions, subjects chose a negative pacing strategy which consists of a significant increase in speed over distance ($F_{(2.165, 23.817)} = 21.568$; $P < 0.001$, $\eta_p^2 = 0.662$).

Effects of response inhibition on perception of effort, HR and blood lactate concentration during the time trial

RPE during the time trial (Fig. 3b) increased similarly over distance in both conditions ($F_{(1.560, 17.158)} = 102.289$; $P < 0.001$, $\eta_p^2 = 0.903$). However, subjects rated a higher perception of effort in the inhibition condition compared to the control condition ($F_{(1, 11)} = 12.156$, $P = 0.005$, $\eta_p^2 = 0.525$).

Heart rate during the warm-up did not differ significantly between conditions ($P = 0.742$, $\eta_p^2 = 0.199$). As expected, HR during the time trial (Fig. 3c) increased significantly over distance ($F_{(1.795,19.744)} = 58.650$; $P < 0.001$, $\eta_p^2 = 0.842$) with no significant difference between the inhibition and the control task ($F_{(1, 11)} = 1.286$; $P = 0.281$, $\eta_p^2 = 0.105$). Similarly, response inhibition did not affect ($F_{(1, 11)} = 0.236$; $P = 0.637$, $\eta_p^2 = 0.021$) the significant increase ($F_{(1, 11)} = 48.825$; $P < 0.001$, $\eta_p^2 = 0.816$) in blood

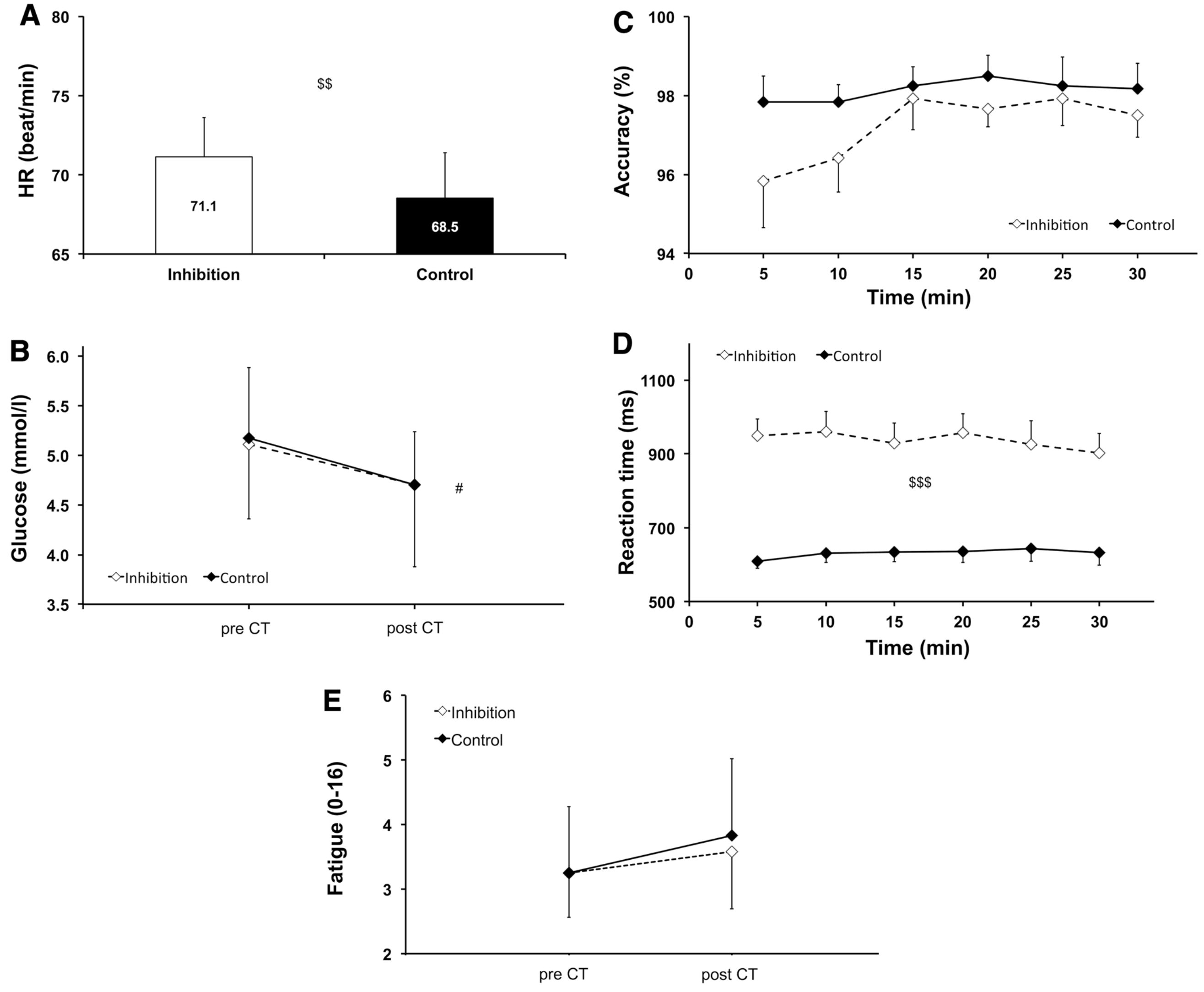

Fig. 2 Effects of cognitive tasks (*CT*) on heart rate (*HR*, **a**), blood glucose concentration (**b**), response accuracy (**c**), reaction time (**d**) and self-reported fatigue (**e**). $^{\$\$}$Significant main effect of condition ($P < 0.01$). $^{\$\$\$}$Significant main effect of condition ($P < 0.001$). $^{\#}$Significant main effect of time ($P < 0.05$). Data are presented as mean ± SEM

lactate concentration observed after the time trial (inhibition condition 1.6 ± 0.4–9.4 ± 4.8, control condition 1.4 ± 0.5–9.0 ± 3.2).

Effects of response inhibition on subjective workload subscales

Cognitive tasks

Subjective workload data related to the cognitive tasks are presented in Fig. 4a. Subjects rated the mental demand ($P = 0.042$, $\eta_p^2 = 0.324$) and effort ($P = 0.009$, $\eta_p^2 = 0.481$) subscales higher in the response inhibition condition. Response inhibition did not have significant effects on the performance, temporal demand and frustration subscales of the NASA-TLX questionnaire.

Time trial

Subjective workload data related to the time trial are presented in Fig. 4b. Subjects rated the time trial as more mentally demanding in the response inhibition condition ($P = 0.005$, $\eta_p^2 = 0.524$) and perceived their performance to be lower in the response inhibition condition ($P = 0.044$, $\eta_p^2 = 0.319$). Response inhibition did not have significant effects on the effort, temporal demand and frustration subscales of the NASA-TLX questionnaire.

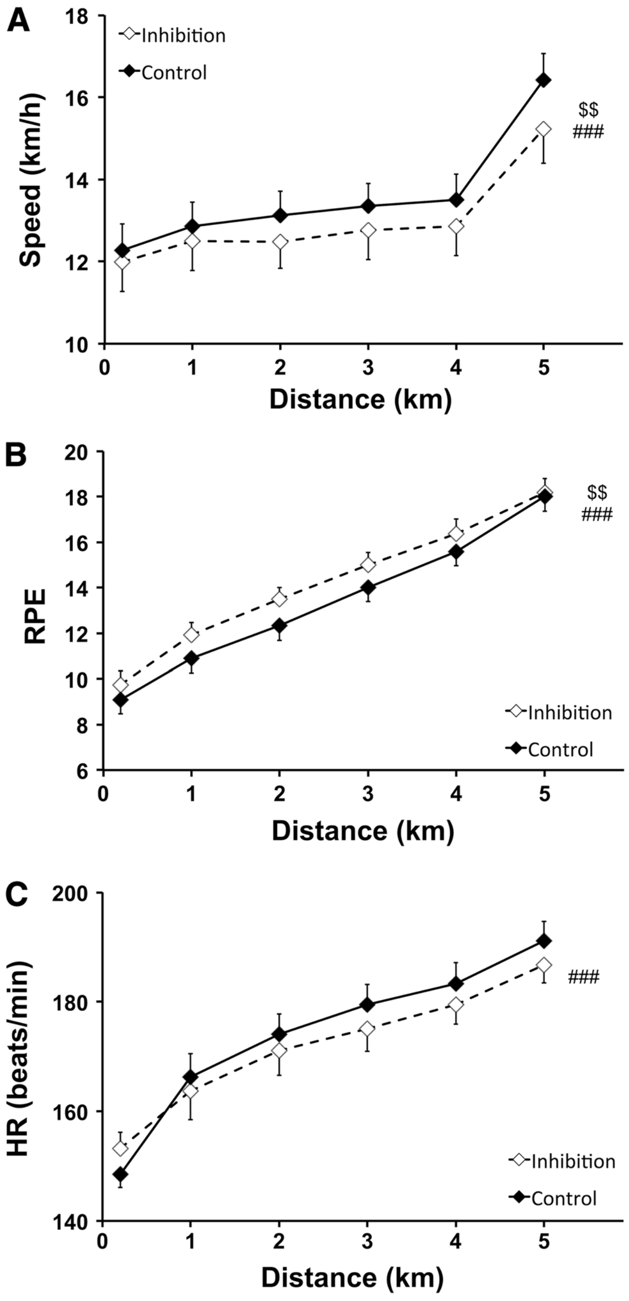

Fig. 3 Effects of cognitive tasks on speed (**a**), rate of perceived exertion (*RPE*, **b**) and heart rate (*HR*, **c**) during the 5-km running time trial. $^{\$\$}$Significant main effect of condition ($P < 0.01$). $^{\#\#\#}$Significant main effect of time ($P < 0.001$). Data are presented as mean ± SEM

Discussion

The aim of our study was to investigate the effects of response inhibition on pacing, perception of effort and endurance performance. In accordance with our hypotheses, results suggest that response inhibition increases perception of effort and impairs endurance performance via a reduction in average speed during the 5-km running time trial. However, response inhibition does not seem to affect the pacing strategy chosen by the subject.

Response inhibition, mental fatigue and endurance performance

The higher HR observed during the inhibition task compared with the control task attests to its more demanding nature (Richter et al. 2008). Moreover, the more demanding nature of the inhibition task was confirmed by the higher mental demand and effort rated by the subjects. However, similar to a previous study (Marcora et al. 2009), blood glucose concentration decreased independently of the nature of the cognitive task. This finding argues against the idea that glucose depletion is the physiological mechanisms underlying the negative effects of mental exertion on subsequent physical or cognitive tasks (Gailliot 2008). The longer reaction time observed during the inhibition task confirms the presence of an additional cognitive process compared to the control task. Because both cognitive tasks included decision-making (selecting an answer) and sustained attention, the longer reaction time during the inhibition task is likely to be related to the response inhibition process (Sugg and McDonald 1994; Stroop 1992). Indeed, contrary to the control task, subjects did not have only to select an answer, but also to inhibit the wrong motor response (e.g. pressing the blue button if the word blue appears in yellow) to select the appropriate one (press the yellow button). Taken altogether, these manipulation checks suggest that we were successful in inducing different levels of mental exertion and response inhibition between the two conditions.

Previous studies using more prolonged mental exertion induced significant mental fatigue defined as an increase in subjective feelings of fatigue and/or a decrease in cognitive performance (Marcora 2010b; Pageaux et al. 2013). Interestingly, in the present study, mental exertion neither induces alterations in cognitive performance (i.e. changes in reaction time and/or accuracy) nor significant changes in subjective fatigue. Also as shown in previous studies, the cognitive tasks induced a significant decrease in vigour (Marcora et al. 2009; Pageaux et al. 2013). The lack of changes in these markers of mental fatigue could be due to the shorter duration of mental exertion in the present study (30 min) compared to previous studies (90 min).

Despite no clear evidence of mental fatigue in the present study, 30 min of mental exertion involving response inhibition had a negative effect on subsequent endurance performance. Indeed, the time to perform the time trial was 6 % longer following the inhibition task compared to the control task. These findings are in agreement with the results of the study by Bray et al. (2008) in which as little as 220 s of mental exertion involving response inhibition was capable of reducing endurance of the handgrip

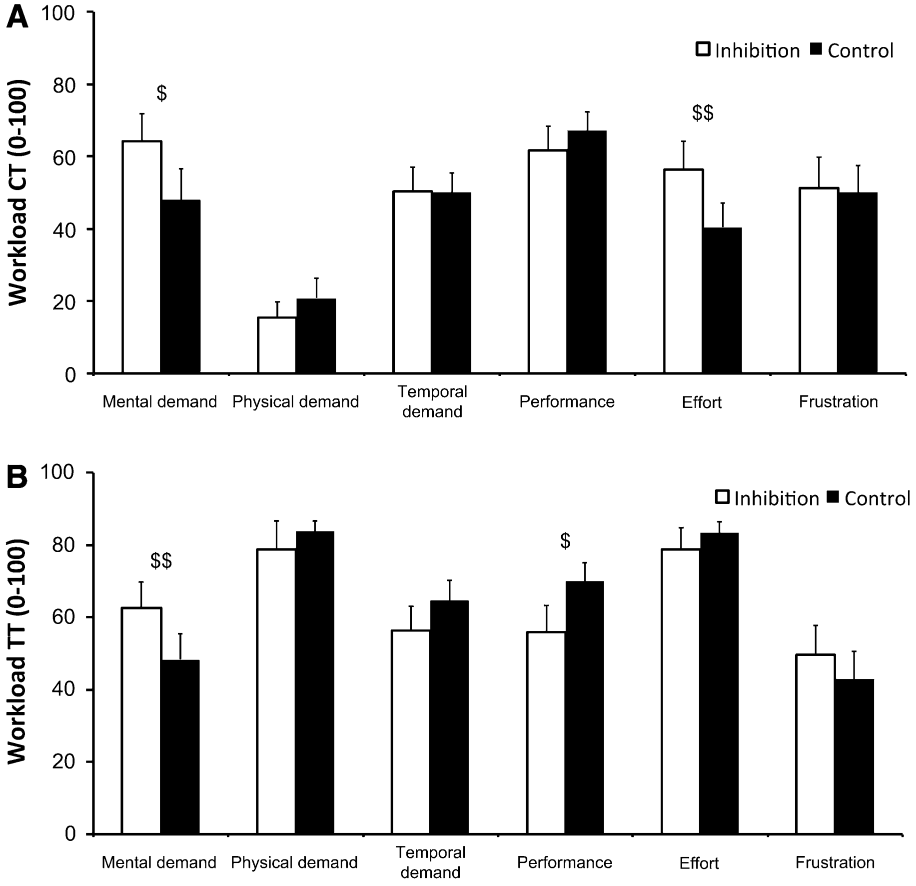

Fig. 4 Effects of cognitive tasks (*CT*, **a**) and 5-km running time trial (*TT*, **b**) on subjective workload (NASA-TLX scale). $^{\$}$Significant effect of response inhibition ($P < 0.05$). $^{\$\$}$Significant effect of response inhibition ($P < 0.01$). Data are presented as mean ± SEM

muscles despite no subjective feelings of mental fatigue. From an applied perspective, it is therefore important to warn coaches and athletes that mental exertion involving response inhibition may have a detrimental effect on subsequent endurance performance even if the athlete does not feel mentally fatigued.

Response inhibition and pacing

The only significant effect of response inhibition on pacing was a reduction in the average running speed chosen by the subject during the time trial. On the other hand, the pacing strategy was not significantly affected by prior mental exertion. In fact, in both the inhibition and control condition, a negative pacing strategy was observed. A negative pacing strategy, defined as an increase in speed over distance, is commonly observed during middle distance events when speed is increased towards the end of both simulated and actual events (for review see Abbiss and Laursen 2008). In fact, the negative pacing strategy observed in our study has been previously observed during 5-km running time trial in both elite (Tucker et al. 2006) and well-trained athletes (Nummela et al. 2006). Because these time trials were conducted on a track, we are confident that the pacing strategy observed in our study is not specific to time trials performed on a treadmill, where speed is changed manually by pressing a button and RPE asked at the end of each kilometre.

This is the first report on the effect of mental exertion involving response inhibition on pacing. However, because of the low performance level of the subjects included in the present study, it is difficult to generalize our findings to competitive endurance athletes. More studies on the effects of mental exertion on pacing are required to investigate whether response inhibition may affect pacing strategy in subjects of higher performance level.

Response inhibition and perception of effort

Previous studies have shown that mentally fatigued subjects perceived endurance exercise as more effortful (Marcora et al. 2009; Pageaux et al. 2013). We have extended these findings by showing that response inhibition is capable of inducing higher perception of effort during subsequent endurance exercise even in the absence of overt mental fatigue.

Because no measurements at brain level were taken in the present study, we can only speculate about the neurobiological mechanisms underlying the negative effect of response inhibition on perception of effort during subsequent endurance exercise. A possible explanation is that 30 min of engagement with the incongruent Stroop colour-word task induced adenosine accumulation in the ACC leading to higher perception of effort during subsequent endurance exercise. This speculation is based on previous human studies showing that the ACC is strongly activated during Stroop tasks involving response inhibition (Bush et al. 1998; Swick and Jovanovic 2002), and that this cortical area is associated with perception of effort (Williamson et al. 2001, 2002). Furthermore, there is experimental evidence from in vitro and animal studies 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). Finally, there is strong evidence that caffeine (an antagonist of adenosine) reduces perception of effort during endurance exercise in humans (Doherty and Smith 2005). Further research in humans and animals is needed to confirm the role of the ACC and brain adenosine in mediating the negative effect of mental exertion on perception of effort and performance during subsequent endurance exercise.

Psychobiological model of self-paced endurance performance

The present findings demonstrate that mental exertion involving response inhibition does not further reduce blood glucose concentration before the time trial, and it does not alter HR immediately before and during the time trial. The blood lactate response to the time trial was also not significantly affected by response inhibition. Therefore, it is unlikely that cardiovascular and metabolic factors can explain the negative effect of response inhibition on endurance performance. Our findings are in accordance with previous observations during time to exhaustion tests. Indeed, it has already been demonstrated the impairment in endurance performance following prolonged mental exertion occurs without any alterations of the cardiorespiratory, metabolic and neuromuscular responses to the exercise (Marcora et al. 2009; Pageaux et al. 2013). Therefore, the negative effect of response inhibition on subsequent self-paced endurance performance is likely to be mediated by other factors.

The psychobiological model of endurance performance (Marcora 2010a) provides a plausible explanation for the negative effect of prior response inhibition on the average running speed chosen by the subject during the time trial. According to this model of endurance performance, the self-regulation of speed/power output during endurance exercise (pacing) is determined primarily by five different cognitive/motivational factors: (1) perception of effort; (2) potential motivation; (3) knowledge of the distance/time to cover; (4) knowledge of the distance/time remaining; and (5) previous experience/memory of perceived exertion during exercise of varying intensity and duration. The effect of previous experience (Factor 5) was controlled in the present study using a randomized crossover design and a familiarization session. Furthermore, in both the inhibition and control conditions, subjects had the same knowledge of the distance to cover (Factor 3) and of the distance remaining (Factor 4). According to the motivation questionnaire, response inhibition did not affect potential motivation (Factor 2). This finding is an agreement with the results of previous studies also showing no significant effect of mental exertion on questionnaires related to potential motivation (Marcora et al. 2009; Pageaux et al. 2013). However, the significantly higher RPE observed after the response inhibition task suggests that response inhibition may affect the willingness to exert effort during subsequent endurance exercise. Furthermore, the psychophysical relationship between RPE and running speed suggests an even greater effect of response inhibition on the perception of effort (Factor 1). Indeed, the effort was perceived higher during the inhibition condition compared to the control condition despite a lower running speed. According to the psychobiological model of endurance performance, the reduction in the average running speed during the time trial is a conscious decision to compensate for the negative effect of response inhibition on perception of effort. Indeed, if the subjects did not choose a lower running speed, the progressive increase in perception of effort over time would have caused premature exhaustion as observed during tests in which the subject could not choose a lower power/torque (Marcora et al. 2009; Pageaux et al. 2013). Because not finishing the time trial is a more negative outcome than completing the time trial in a longer time, reducing the average running speed was the most appropriate behavioural response.

Conclusions and practical perspectives

The present study provides the first experimental evidence that self-paced endurance performance can be altered by prior mental exertion involving response inhibition. This negative effect was associated with a reduction in average running speed chosen by the subject during the time trial. However, pacing strategy was not affected by prior mental exertion involving response inhibition. Importantly, this study suggests that performing only 30 min of mental exertion can reduce endurance performance without any subjective feeling of mental fatigue at rest. Therefore, athletes and coaches should avoid any cognitive tasks involving response inhibition process before competition, such as controlling anger during pre-event interviews with nosy journalists. Furthermore, the results of the present study suggest that monitoring of RPE during endurance training sessions may be a more sensitive measure to identify mental fatigue than administering generic mood questionnaires. Because monitoring fatigue states is important to prevent non-functional overreaching and overtraining in endurance athletes (Nederhof et al. 2008), more applied research in this area is warranted.

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

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