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Interactions between perceived exertion and thermal perception in the heat in endurance athletes

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ABSTRACT

Introduction: The study aimed to investigate how a distortion of perceived exertion in the heat may affect, during a self-paced cycling exercise preceded by prior cognitive task, the thermal perception and the subsequent regulation of power output in high level athletes.

Methods: Eleven endurance trained male athletes completed four experimental sessions including a 30-min fixed-RPE (15-Hard) cycling exercise in neutral (TMP-22 °C) and hot (HOT-37 °C) conditions, following a 60-min incongruent Stroop task (EXP) or passively watching documentary films (CON). Central and peripheral performances of the knee extensors were assessed before the cognitive task and after the exercise.

Results: Although mental demand and effort were higher in EXP ($P < 0.05$), no effect of prior cognitive task was observed on subjective feelings of mental fatigue or decline in power output at a fixed RPE. Average exercise intensity was lower in HOT than TMP ($3.14 \pm 0.09\,W{\cdot}kg^{-1}$ *vs.* $3.42 \pm 0.10\,W{\cdot}kg^{-1}$ respectively, $P < 0.05$). Skin temperature and warmth sensations were higher in HOT throughout the exercise ($P < 0.05$) but not thermal comfort. Central and peripheral parameters were not affected more in HOT than in TMP.

Conclusion: Although the effects of combined stressors on the distortion of perceived exertion could not be verified, the greater decline in power output recorded in HOT than TMP suggest a high contribution of both perceptual and cardiovascular responses in the regulation of work rate when the subject is in mild hyperthermia.

1. Introduction

Performance level in prolonged self-paced exercise decreases as the ambient temperature increases (Tucker et al., 2004). Impaired endurance performance under heat strain is usually associated with a series of physiological alterations (*i.e.* neuromuscular, cardiovascular and metabolic; Nybo et al., 2014) mediated by the increase in core temperature (T_{CO}), but also by the distortion of perceptual responses (Flouris and Schlader, 2015). Perceived exertion is the conscious awareness of work required to complete a physical task (Pageaux, 2016). Harder subjective effort rated at a given workload in the heat potentially explains behavioral-induced reductions in exercise intensity. In this context, understanding the mechanisms regulating the perceptual responses during self-paced exercise requires the utilization of exercise models in which subjects are free to vary the work rate. Indeed, the behavioral regulation of muscle activity presumably aims to protect homeostasis from excessive changes in T_{CO} (Davies et al., 2016).

The regulation of exercise intensity by sustaining a given rating of perceived exertion (RPE) value outlined the higher linear rate of power output (PO) decline in the heat (*i.e.* 35 °C *vs.* 15 and 25 °C), concomitant to a greater heat storage during the first minutes of the exercise (Tucker et al., 2006). The authors stated that muscle activity was regulated subconsciously in anticipation to excessive-induced disturbances in homeostasis (Saint Clair Gibson et al., 2006). However, in a similar protocol, a recent study using direct calorimetric measurements challenged this hypothesis (Friesen et al., 2018). Nevertheless, there is evidence that skin temperature (T_{SK}) rather than T_{CO} is a predominant signaling input modulating perceived exertion in the heat through thermal perception (Schlader et al., 2011). Dynamic interactions between cutaneous thermal afferences and perceptual responses should,

Abbreviations: ANOVA, Analysis of Variance; HR, Heart Rate; MVC, Maximal Voluntary Contraction; NASA-TLX, National Aeronautics and Space Administration Task Load Index; PO, Power Output; PPO, Peak Power Output; RH, Relative Humidity; RPE, Rating of Perceived Exertion; VT1, First Ventilatory Threshold; VT2, Second Ventilatory Threshold; T_{CO}, Core Temperature; T_{SK}, Skin Temperature; VAL, Voluntary Activation Level

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however, be examined. Indeed, the manipulation of ambient temperature during a prolonged self-paced exercise showed no synchronicity between RPE and real-time changes of T_{SK} and subsequent thermal sensation (Hartley et al., 2012).

When exercising in hot condition, changes in warmth sensation modify comfort perception (classically, the warmer the more uncomfortable) and may induce, by this way, a subsequent alteration in RPE (Schulze et al., 2015). Whether additional mental fatigue influences comfort perception and RPE when exercising in the heat remains to be determined (Acevedo and Ekkekakis, 2001). The combined stress factors imposed by heat strain and the cognitive demand required for pace control might have interactive (*e.g.* additive, synergistic or antagonistic) effects on the distortion of RPE and subsequent PO (Lloyd and Havenith, 2016). In neutral conditions, mental fatigue resulting from prior prolonged cognitive activity may lead to lower endurance performance (Van Cutsem et al., 2017a). Pageaux et al. (2013) reported no effect of mental fatigue on neuromuscular performance, suggesting that the subsequent decrease in endurance performance is mainly regulated through a higher RPE rather than a lower ability to produce force. This finding has been confirmed by De Morree et al. (2012) who indicated an increase in RPE in response to the greater demand from the central motor command in fatigued state. Thereafter, no similar consensus was verified in recent studies involving both mental fatigue and heat stress before and/or during endurance exercise (Otani et al., 2016; Van Cutsem et al., 2017b).

Within this framework, the purpose of this experimental work was to compare how a distortion of perceived exertion from prior mental fatigue (EXP) may affect thermal perception and subsequent regulation of cycling PO at fixed RPE, during an exercise performed either in neutral (TMP, 22 °C) or hot (HOT, 37 °C) ambient condition. Although the maintenance of a constant subjective intensity limits the level of physiological disturbance (Lander et al., 2009), neuromuscular alterations induced by prolonged heat exposure could however mediate a greater slow-down regulation of PO (Goodall et al., 2015). To prevent their occurrence, we sought to use a limited exercise duration (30-min) rather than ending the trial when a PO threshold is reached (Tucker et al., 2006). In the same way, central and peripheral mechanisms contributing to fatigue developments were also monitored by comparing pre- and post-exercise measurements. Lastly, endurance athletes were recruited to reduce the high inter-individual variability of heat-induced physiological and psychological stresses (Tikuisis et al., 2002).

We hypothesized that during an exercise at fixed RPE, prior cognitive exertion (EXP *vs.* CON) or heat exposure (HOT *vs.* TMP) both might decrease PO. This reduction in PO might be exacerbated by the combined effects of both stressors. The PO regulation might be mediated by a significant distortion of perception of effort and warmth, whereas the contribution of neuromuscular (*i.e.* central and peripheral) alterations would not be significant.

2. Material and methods

2.1. Participants

Eleven competitive-level male athletes in cycling and triathlon (age: 27.0 ± 8.6 years; height: 1.79 ± 0.09 m; body weight: 70.0 ± 7.7 kg; maximal aerobic power: 346 ± 56 W; maximal oxygen uptake: 63 ± 5 mL· min^{-1}·kg^{-1}) participated to the current study. According to the inclusion criteria, subjects were free of any mental, somatic or cardio-respiratory disorders and not accustomed to hot environment. Athletes were classed in the performance level 3 or 4, according to guidelines for subject's classification in sports science research (De Pauw et al., 2013). All experimental procedures conformed to the Declaration of Helsinki were approved by the local ethics committee. All athletes received written instructions outlining all procedures and gave written informed consent but were naïve of the aims and hypothesis. A reward (*i.e.* sports store-voucher) was given at the end of the last session to maintain the highest possible motivation during all the experimental procedure.

2.2. Experimental procedure

Each athlete visited the laboratory on five separate occasions (20–22 °C ambient temperature and 40–50% relative humidity) at the same time of the day (± 2 h). Sessions were all conducted during the winter season in the northern hemisphere (*i.e.* from November to March) and were completed within 5 weeks for a given subject with a minimum period of 72 h between visits. Each athlete received written instructions to sleep for at least 7 h, avoid strenuous exercise, drink a sufficient volume of water, limit consumption of caffeine, nicotine or alcohol for 24 h prior to each session and have the same diet for the two meals preceding each session.

To limit under or over-estimation during the experimental protocol (Eston et al., 2015), the ability to cycle at a constant RPE was assessed in the inclusion visit during two 5-min exercise bouts corresponding to a RPE-15 level on the 6–20 Borg Scale (Pageaux, 2016). An appropriate coefficient of variation (< 5%) for test-retest reliability of PO was required. Athletes then completed a maximal cycling test to determine peak power output (PPO) after 6-min warm-up at 100 W + increments of 30 W per 2 min-stage until exhaustion using an electronically braked cycle ergometer (Schoberer Rad Messtechnik, Jülich, Welldorf, Germany). During this test, heart rate (HR, RS800, Polar, Finland) and respiratory gas exchanges were analyzed using breath-by-breath gas analyzer (Oxycon, Jaeger, Germany). Exercise stopped when the athletes reached volitional exhaustion, defined as the point at which they were unable to maintain a pedal cadence of 60 rpm for 30 s despite verbal encouragement. PPO was calculated with the formula $PPO = PO_{out} + (t/120) \times 30$ (PO_{out}: workload of the last completed stage; *t*: time (s) in the final stage). The first (VT1) and the second (VT2) ventilatory thresholds were determined independently by two investigators according to the criteria previously described (Beaver et al., 1986).

During the four next experimental visits, athletes performed a 60-min cognitive task (refer to *Cognitive task* part for more details), either mentally strenuous (EXP) or control (CON), followed by a cycling exercise (refers to *Cycling Exercise* part for more details) in either neutral (TMP; 22.5 ± 1.7 °C, 49.8 ± 10.3% of relative humidity (RH)) or hot (HOT; 37.2 ± 1.7 °C, 37.5 ± 6.8% RH) ambient conditions (Fig. 1). All sessions (*i.e.* EXP_{TMP}, EXP_{HOT}, CON_{TMP} and CON_{HOT}) were distributed in a randomized and counterbalanced order. Following urine sampling and a standardized 5-min warm-up, neuromuscular assessment of right knee extensors was completed (refers to *Neuromuscular assessment* part for more details). After instrumentation with physiological measuring sensors, the athlete was seated in front of a personal computer in a temperate and quiet room for the completion of the cognitive task. At least 20 min after completion of the cognitive task and following a standardized 5-min warm-up in neutral ambient condition, the athlete went into an environmental chamber to perform the cycling protocol. Ambient temperature and humidity were continuously controlled with a specific probe fixed at the level of the athlete's head in his riding position (Testo, Forbach, France). No forced wind exposure and no hydration were applied during the trial. Neuromuscular assessment was repeated at the end of cycling exercise.

2.2.1. Neuromuscular assessment

The athlete sat upright in a custom built chair with hips at 100° of flexion and knees at 90° and was secured with non-compliant straps to minimize body movement. A calibrated force transducer (F 501 TC 200 daN, TME 78 Orgeval, France) was used to record the mechanical responses during maximal voluntary contractions (MVC) and electrically evoked contractions. Surface electromyographic signals were continuously recorded from the *vastus lateralis* with a pair of self-adhesive surface (10-mm diameter) electrodes (Controle Graphique Medical, Brie-Comte-Robert, France) in bipolar configuration with a 20-mm

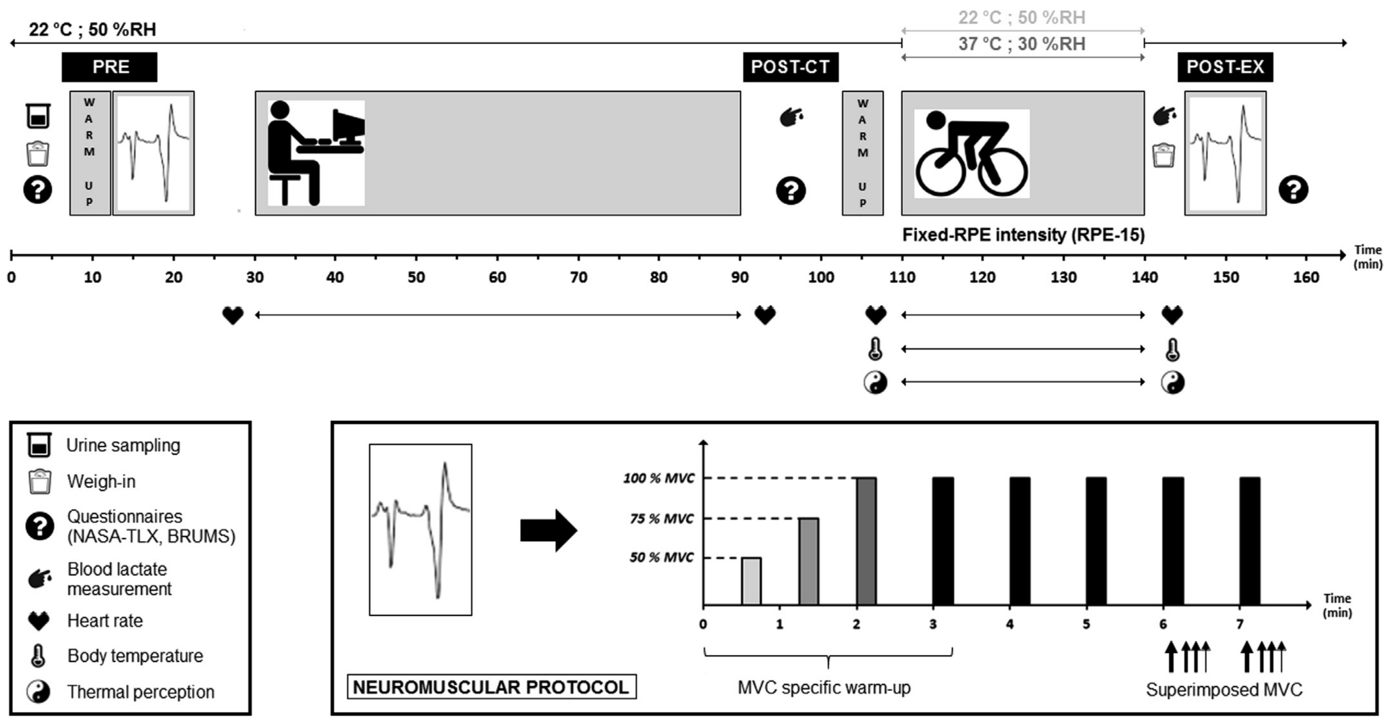

Fig. 1. Overview of the experimental protocol. Order and timing were similar for each visit. *RH* = relative humidity, *MVC* = maximal voluntary contraction, *BRUMS* = Brunel Mood State survey, *NASA-TLX* = National Aeronautics and Space Administration Task Load Index rating scale, *RPE* = Rating of Perceived Exertion.

inter-electrode distance. The reference electrode was fixed on the patella. Signals were amplified with a bandwidth frequency ranging from 1 Hz to 5 kHz (common mode rejection ratio = 110 dB, impedance input = 1000 MΩ, gain = 1000), digitized on-line at a sampling rate of 2000 Hz and finally stored for analysis using a commercially available software (Acqknowledge 4.1, Biopac Systems Inc.).

Transcutaneous electrical stimulations were delivered to the right femoral nerve using a self-adhesive electrode cathode (10-mm diameter) pressed manually by the same trained experimenter. The self-adhesive rectangular anode (50 × 90 mm, Dura-Stick premium, Compex) was placed in the gluteal fold. A constant current stimulator (model DS7A, Digitimer, Hertfordshire, UK) delivered a square wave stimulus of 1-ms duration and 400-V maximal voltage. During the preliminary testing session, individual supramaximal stimulation intensities were determined and ranged from 80 mA to 130 mA. After a specific quadriceps isometric warm-up, the athlete performed neuromuscular protocol as follows: (i) 4-s MVC without superimposed stimulation, (ii) 4-s MVC with superimposed supramaximal 100-Hz doublet stimulus, followed 2 s later by paired potentiated 10-Hz (Db_{10}) and 100-Hz (Db_{100}) doublets stimuli, and single potentiated twitch (Tw_p) in the relaxed muscle. Each step was repeated a second time after a 45-s rest period.

Each neuromuscular parameter was averaged from the two repetitions. Peripheral fatigue component analysis included Tw_p, M-wave peak-to-peak amplitude (M-wave) and the low-to-high frequency doublet ratio ($Db_{10:100}$). Force production during MVC was calculated for each 0.25-s trial upon reaching the force plateau. Voluntary Activation Level (VAL) was assessed by twitch interpolation method. The amplitude of the superimposed doublet elicited during MVC was compared with that of the control Db_{100} in relaxed muscle using the following equation:

$$VAL = \left[1 - \frac{Superimposed\ doublet}{Db100}\right] \times 100$$

2.2.2. Cognitive task

The EXP task consisted in completing a modified incongruent version of the Stroop color-word task during 60 min. The computerized version of the task performed in this protocol was programmed with E-Prime software (PST, Sharpsburg, PA, USA) and complied with the description made in a previous study (Pageaux et al., 2015).

The CON task consisted in watching documentary programs chosen by the experimenters, "The Perfect Runner, Clearwater Documentary Inc., 2012" and "Miracle Body, NHK Joho Network, 2008", in continuous and under the same viewing conditions as the experimental task.

2.2.3. Cycling exercise

Athletes performed 30-min of cycling on an air-braked cycle ergometer (Wattbike, Wattbike LTD, Nottingham, UK) previously validated (Hopker et al., 2010). They were instructed to cycle at a PO individually perceived as a whole-body hard effort (*i.e.* RPE-15 level on the Borg 6–20 scale) and were advised to reevaluate regularly their RPE to adjust PO. Cadence and resistance level were freely adjusted by the participant and no feedback was provided regarding time, distance covered, PO or any physiological value. Cycling values were continuously recorded every 5 s. The first 3 min of exercise were retained for analysis. Then, the last minute of each 3-min interval was retained to calculate the corresponding PO and further analyze the rate of PO decline throughout the exercise.

2.3. Psychological and physiological measurements

The Brunel Mood Scale survey (Terry et al., 2003) was used to quantify current mood before and after the cognitive task, in accordance with a recent study of Pageaux et al. (2015). "Fatigue" and "Vigor" subscales were considered as markers of mental fatigue.

Subjective load was assessed immediately after the cognitive task and the cycling exercise through a simplified version of the National Aeronautics and Space Administration Task Load Index (NASA-TLX) rating scale (Hart and Staveland, 1988).

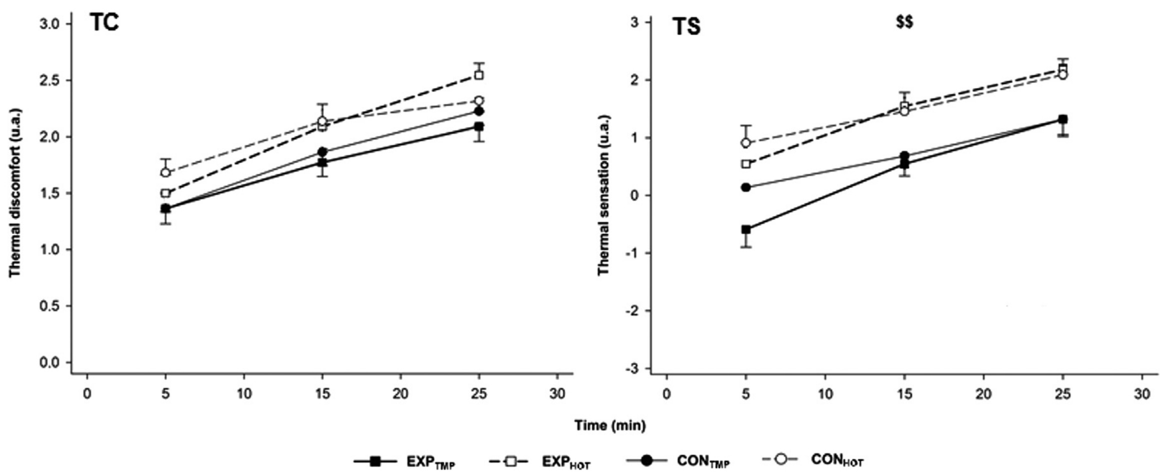

Fig. 2. Overall mean thermal discomfort (*TC*) and thermal sensation (*TS*) over cycling exercise. Thick lines and square plots represent values reported during exercise following incongruent Stroop task (EXP). Thin lines and circle plots represent values reported during exercise following passive control task (CON). Solid lines and black plots represent values reported in neutral environment (TMP). Dotted lines and white plots represent values reported in hot environment (HOT). $^{\$\$}$Significant effect of ambient condition on mean values (TMP < HOT, $P < 0.05$).

Thermal and comfort sensations were assessed using visual analog scales at three time periods (5, 15 and 25-min) of cycling exercise. Participant was instructed to reply to the question "How do you perceive the current thermal environment?" on a visual analog scale ranging from −3 "very cold" to 3 "very hot" to determine comfort sensation. Subjective comfort was determined in response to the question "Do you feel comfortable in the current thermal environment?" and rated from 0 "comfortable" to 3 "very uncomfortable" (Gagge et al., 1969).

Hydration status was controlled at the beginning of each experimental session by assessing the urine specific gravity (*i.e.* ≤ 1.02 g·mL^{-1}). Capillary blood samples were collected from ear lobes before the warm-up and at the end of the cycling exercise. Lactate concentration ([La-]) was measured from capillary blood samples using a Lactate Pro System (LT-1710, Elitech, Puteaux, France).

Heart rate values were collected every 5 s during the whole pre-exercise task and during the cycling session by using a telemetric monitor (Garmin Pro, Garmin, USA).

Body temperature (T_{CO} and T_{SK}) values were monitored throughout the entire cycling exercise. Core temperature was assessed in the gastro-intestinal region, with a pre-calibrated ingestible electronic sensor (E-Celsius©, Bodycap Medical, France; dimensions 17.2 × 8.2 mm; weight 1.7 g; accuracy ± 0.1 °C) previously validated for assessing human temperature (Chapon et al., 2012). Data were continuously transmitted every 30 s to a specific monitor (E-Celsius© Performance, Bodycap Medical). The capsule was ingested at the same time (± 1 h) in a 6–12 h window before each trial. Skin temperature was recorded every 15 s with pre-calibrated insulated Pt-100 temperature probes (Grant Instruments Ltd, Cambridge, UK; length 18 mm; accuracy ± 0.3 °C) fixed on 4 sites (left part of the chest, right lower arm, right upper thigh and left calf) with surgical tape and bandage, according to a four-site measurement model (Ramanathan, 1964).

2.4. Statistical analysis

All data are presented as mean ± SD. Normal distribution was systematically checked using Shapiro-Wilk's test. Degrees of freedom were adjusted using the Greenhouse-Geisser correction when violations of sphericity were present.

Paired T-tests were used to test potential differences in accuracy and reaction time between EXP and CON. Two-way analysis of variance (ANOVA; time x cognitive condition) for repeated measures were conducted to detect any potential differences in HR and subjective load. Two-way ANOVAs (cognitive condition × environmental condition) were conducted to detect any differences in mood parameters before (PRE) and after (POST-CT) the cognitive task, and in [La-], cognitive load and neuromuscular performances before (PRE) and after (POST-EX) the cycling exercise. Paired T-tests were also applied in the following parameters to detect pre-post differences (PRE *vs.* POST-CT, PRE *vs.* POST-EX). Similarly, two-way ANOVAs were conducted to analyze the physical, psychological and physiological dependent variables recorded during the cycling exercise.

Pairwise comparisons using a Tukey's HSD were conducted when significant differences were observed. When an interaction between conditions was observed in conjunction with a significant effect of one or another condition, paired T-tests were conducted to examine instantaneous or time effect. For all statistical analysis, the significance level was set at a 95% confidence level ($P < 0.05$). Effect size was calculated as partial-eta-squared (ηP^2) and interpreted using the following criteria: no effect if $0 \leq \eta P^2 < 0.05$, minimal effect if $0.05 \leq \eta P^2 < 0.26$, moderate effect if $0.26 \leq \eta P^2 < 0.64$, strong effect if $\eta P^2 \geq 0.64$ (Ferguson, 2009). Statistical analysis was performed using Statistica software (Statistica version 8.0 for Windows, Statsoft, Tulsa, OK, USA).

3. Results

3.1. Perceptive and cognitive responses

Reaction time (0.921 ± 0.212 s *vs.* 0.928 ± 0.245 s; $P = 0.941$) and accuracy of responses to the Stroop task (94.8 ± 5.2% *vs.* 94.7 ± 5.3%; $P = 0.950$) were similar between EXP_{TMP} and EXP_{HOT}, respectively.

Subjective workloads related to cognitive tasks are presented in Fig. 2. The EXP sessions increased the mental demand ($P < 0.001$, $\eta P^2 = 0.297$) and effort ($P = 0.002$, $\eta P^2 = 0.206$) compared to CON sessions. Conversely, the mood surveys did not show any effect of the EXP or CON sessions on Fatigue subscale between PRE ($P = 0.519$, $\eta P^2 = 0.010$) and POST-CT ($P = 0.768$, $\eta P^2 = 0.002$). Similarly, Vigor subscale was not affected by the cognitive tasks as indicated by PRE ($P = 0.585$, $\eta P^2 = 0.008$) and POST-CT ($P = 0.860$, $\eta P^2 < 0.001$) measurements. Repeated cognitive sessions induced similar subjective workload and mood scores (all $P > 0.05$).

Variations in thermal perception (*i.e.* sensation and comfort) during the cycling exercise were not affected by the type of pre-exercise cognitive task ($P > 0.05$; Fig. 3). Heat sensation was higher in HOT

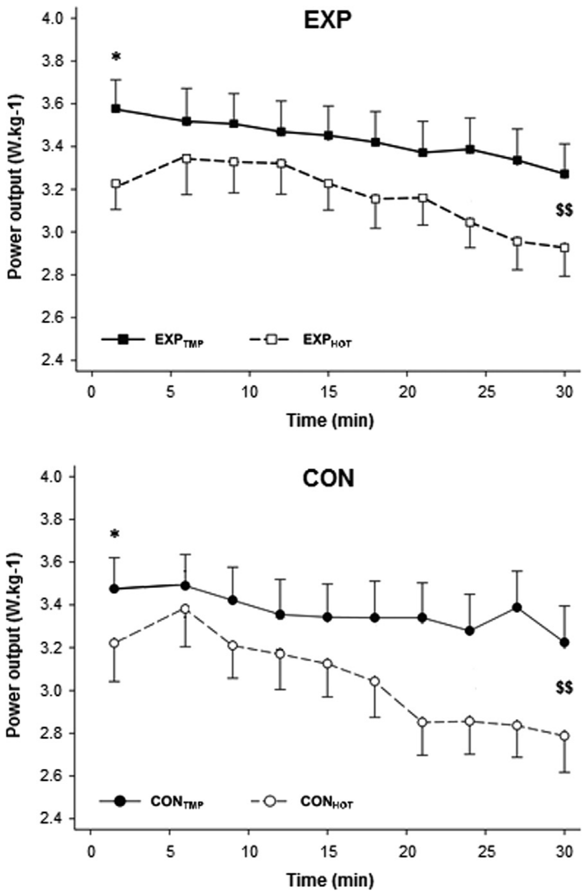

Fig. 3. Mean power output (*PO*) variations throughout cycling exercise. Measurements following incongruent Stroop task (EXP) and passive control task (CON). Solid lines and black plots represent values assessed in neutral condition (TMP). Dotted lines and white plots represent values assessed in hot condition (HOT). *Significant effect of ambient condition on initial PO values (TMP > HOT, P < 0.05). $$Significant effect of ambient condition on the rate of PO decline (TMP < HOT, *P* < 0.05).

condition ($P < 0.001$, $\eta P^2 = 0.285$), whereas thermal discomfort was not altered between conditions ($P = 0.253$, $\eta P^2 = 0.032$).

No interaction between cognitive conditions and subjective workload parameters was recorded after the cycling exercise (all $P > 0.05$). Only "Effort" was scored higher in HOT condition ($P = 0.003$, $\eta P^2 = 0.350$).

3.2. Physical responses

The cognitive tasks had no effect on mean PO ($P = 0.501$, $\eta P^2 = 0.011$) and the rate of PO decline ($P = 0.914$, $\eta P^2 < 0.001$; Fig. 4) both in TMP and HOT conditions. Mean PO was higher in TMP (3.46 ± 0.44 and 3.39 ± 0.49 W·kg^{-1} in EXP$_{TMP}$ and CON$_{TMP}$, respectively; $P = 0.047$, $\eta P^2 = 0.095$) compared to HOT (3.20 ± 0.40 and 3.09 ± 0.47 W·kg^{-1} in EXP$_{HOT}$ and CON$_{HOT}$, respectively). Moreover, the rate of PO decline was faster in HOT (-0.019 ± 0.017 and −0.024 ± 0.022 W·kg^{-1}·min^{-1} in EXP$_{HOT}$ and CON$_{HOT}$, respectively; $P = 0.015$, $\eta P^2 = 0.138$) than in TMP (–0.009 ± 0.013 and −0.007 ± 0.015 W·kg^{-1}·min^{-1} in EXP$_{TMP}$ and CON$_{TMP}$, respectively).

The cognitive task had no effect on PRE and POST-EX measurements for all neuromuscular parameters considered (all $P > 0.05$; Table 1). The decrease of MVC between PRE and POST-EX was significant in CON$_{TMP}$ only (−6.7 ± 3.7%, $p < 0.05$) but not in the other conditions (−0.4 ± 11.1%, −2.6 ± 6.9%, −3.5 ± 7.2% in EXP$_{TMP}$, EXP$_{HOT}$, CON$_{HOT}$, respectively). The decrease of VAL was also significant in CON$_{HOT}$ only (-4.3 ± 4.2%, $P < 0.05$), but not in the other conditions (−2.0 ± 6.8%, −1.8 ± 6.1%, −2.0 ± 5.6% in EXP$_{TMP}$, EXP$_{HOT}$, CON$_{TMP}$, respectively).

3.3. Physiological responses

Heart rate values were not different between EXP and CON (66.5 ± 9.5 and 66.7 ± 10.1 bpm, respectively; $P = 0.977$, $\eta P^2 < 0.001$). Moreover, repeated cognitive sessions induced similar HR responses for both tasks ($P = 0.101$, $\eta P^2 = 0.142$).

During cycling exercise, no effect of both cognitive task and ambient conditions was observed on the HR increase ($P > 0.05$). At the end of the exercise, HR was similar ($P > 0.05$) regardless of the condition (176.5 ± 11.5, 175.5 ± 11.7, 179.0 ± 10.8 and 176.3 ± 9.1 bpm in EXP$_{TMP}$, CON$_{TMP}$, EXP$_{HOT}$ and CON$_{HOT}$, respectively). Reached HR values corresponded to 91–94% of maximal HR.

Lactate values assessed before exercise were not different between conditions. Post-exercise measurements indicated an effect of ambient condition (TMP > HOT; $P = 0.030$, $\eta P^2 = 0.113$). An increased [La-] at post-exercise "Effort" was scored higher in HOT condition ($P < 0.05$). Post-exercise [La-] were respectively 4.5 ± 2.4, 3.8 ± 2.6, 3.0 ± 1.8 and 2.5 ± 1.4 mmol·L^{-1} in EXP$_{TMP}$, CON$_{TMP}$, EXP$_{HOT}$ and CON$_{HOT}$.

The cognitive task had no effect on thermoregulatory variables recorded during the cycling exercise (*i.e.* T_{CO} and T_{SK} variations; $P > 0.05$; Fig. 5). During the exercise, T_{CO} increased but no effect of ambient conditions was observed on the rate of increase (0.06 ± 0.01, 0.04 ± 0.01, 0.05 ± 0.01 and 0.05 ± 0.01 °C·min^{-1} in EXP$_{TMP}$, CON$_{TMP}$, EXP$_{HOT}$ and CON$_{HOT}$, respectively; $P > 0.05$). At the end of the exercise, T_{CO} values were similar ($P > 0.05$) regardless of the condition. During the first 3-min of the exercise, mean T_{SK} values were significantly higher in HOT than in TMP ($P < 0.001$, $\eta P^2 = 0.569$). The increase in T_{SK} over the cycling exercise was influenced by ambient conditions (0.06 ± 0.01 and 0.06 ± 0.01 °C·min^{-1} in EXP$_{HOT}$ and CON$_{HOT}$ *vs.* 0.03 ± 0.01 and 0.02 ± 0.01 °C·min^{-1} in EXP$_{TMP}$ and CON$_{TMP}$, respectively; $P < 0.001$, $\eta P^2 = 0.241$).

4. Discussion

The purpose of this study was to examine the combined effects of cognitive exertion and heat strain on the distortion of perceptual parameters through the regulation of PO at a fixed RPE during a cycling exercise. In this way, a self-regulated cognitive task (*i.e.* incongruent Stroop task) alternatively performed in TMP and HOT conditions was utilized in an attempt to induce mental fatigue before cycling exercise. The absence of higher mental fatigue following EXP did not allow verification whether thermal perception and PO regulation may be modulated by cognitive afferences in endurance athletes. However, whatever the cognitive condition, exercising in HOT decreased PO compared to TMP whereas T_{CO} and post-exercise muscle capacities were similar between conditions. The results from this experiment suggest that, during exercise in mild hyperthermia, cardiovascular and perceptual responses to the heat are probably the main factors influencing perceived exertion.

The high correlations with HR, ventilation and oxygen consumption support the use of RPE as a relevant tool to regulate exercise intensity (Thompson et al., 2014). In our study, the athletes sustained a 15-RPE equivalent intensity for 30 min corresponding to 70.6 ± 5.6, 69.0 ± 6.2, 65.2 ± 4.0 and 62.9 ± 5.6% PPO in EXP$_{TMP}$, CON$_{TMP}$, EXP$_{HOT}$ and CON$_{HOT}$, respectively. Moreover, as inferred through post-exercise variations in [La-] (*i.e.* 3.0 ± 0.7, 2.8 ± 0.7, 1.7 ± 0.6 and 1.2 ± 0.5 mmol·L^{-1} in EXP$_{TMP}$, CON$_{TMP}$, EXP$_{HOT}$ and CON$_{HOT}$, respectively), the cycling exercise was performed around PO between VT1 and VT2 (*i.e.* 77.8 ± 8.8% of PO produced at VT2). Compared with extrapolated data from previous similar experimental protocols (Tucker et al., 2006), the workload imposed on the athletes could be considered hard enough to require significant behavioral regulation of

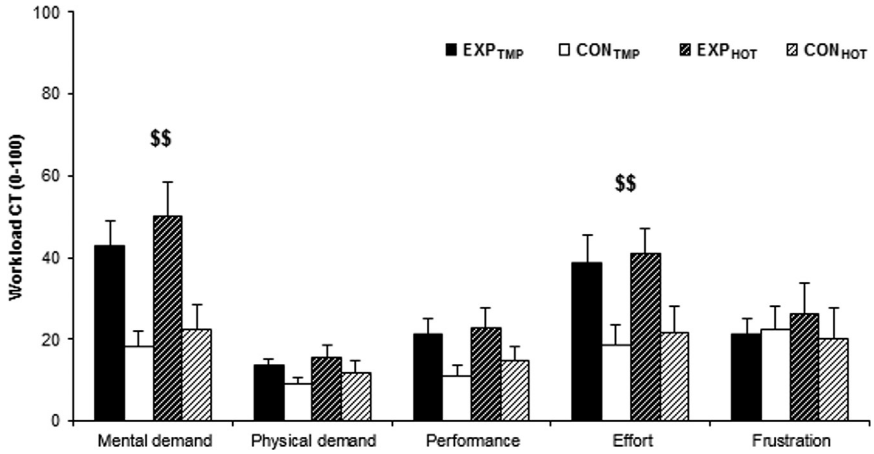

Fig. 4. Subjective workload induced by the cognitive task. Measurements following the incongruent Stroop Task (EXP, black columns) and the passive control task (CON, white columns). $$Significant main effect of the cognitive task type (EXP > CON, $P < 0.05$).

PO at a fixed RPE.

Contrary to our initial hypotheses, the results derived from this study did not verify a significant effect of EXP on thermal perception and PO regulation at a fixed RPE. The induction of mental fatigue in our experimental protocol aimed to investigate the psychological and/or behavioral adaptive mechanisms initiated to regulate thermal perception and PO. With regard to mood parameters, both cognitive tasks induced negative but small and similar variations in Fatigue and Vigor levels. Moreover, similar HR responses raise questions on the cognitive challenge induced by EXP (Richter et al., 2008). One possible explanation of these divergent results is that the 60 min incongruent Stroop Task could have not been sufficiently stressful to induce mental fatigue, despite its challenging nature reflected by higher mental demand and effort than in CON. The cognitive performance of highly trained athletes (*i.e.* performance level 3–4; De Pauw et al., 2013) participating in this study could have not been affected by a progressive decreased arousal and motivation (Martin et al., 2016). Higher ability to bypass irrelevant stimuli (*i.e.* inhibition) observed in endurance athletes suggests a reduced cognitive demand (Cona et al., 2015), compared with less trained populations for which mental fatigue and/or decreased endurance performance were observed following EXP (Pageaux et al., 2015; Otani et al., 2016). Another explanation is that the passive and monotonous character of the control task involved similar changes in subjective fatigue and vigor than EXP (Wascher et al., 2014; Huang et al., 2015). In addition, methodological limitations including the low sensitivity of Brunel Mood State questionnaire to small short-term changes of mental fatigue, and the absence of control from a basic cognitive task repeated before and after EXP or CON, might have led to an underestimation of mental fatigue following both conditions (Van Cutsem et al., 2017a). Finally we can hypothesize that in highly trained endurance athletes, the combined cognitive and environmental stressors proposed in this study were not strong enough to alter the work rate during a prolonged cycling exercise (Lloyd and Havenith, 2016).

Regardless of prior cognitive activity, the current results are in line with literature data showing higher-than-normal RPE in the heat (Flouris and Schlader, 2015). This study is one of the first to report a lower PO from the beginning of the exercise in HOT compared to TMP (*i.e.* 3.23 *vs.* 3.53 $W \cdot kg^{-1}$). This early difference in PO between HOT and TMP conditions might be explained by the increased T_{SK} (+ 0.2–0.3 $°C \cdot min^{-1}$) and subsequent changes in heat sensations in HOT. As observed in previous studies, a faster rate of PO decline was also recorded in HOT condition (Tucker et al., 2006; Friesen et al., 2018). Perceptual disturbances are frequently associated, in this context, with impaired supraspinal ability to produce muscular force (Goodall et al., 2015). On the contrary, the current lack of post-exercise MVC and VAL reduction in most of the experimental conditions suggests that peripheral alterations from cycling exercise at fixed RPE (*i.e.* decreased Tw_p and $Db_{10:100}$) were probably insufficient to exacerbate central fatigue. Indeed, despite greater skin blood flow and subsequent cardiovascular strain highlighted by higher core-to-skin temperature gradient in HOT (Sawka et al., 2011), blood [La-] recorded in the current study suggest a greater contribution of the anaerobic metabolism in TMP. The reduced metabolic challenge induced by fixed-RPE exercise in HOT probably contributes to minimize subsequent fatigue (Lander et al., 2009). Moreover, the limited increase in T_{CO} recorded after 30 min of exercise in HOT (*i.e.* 38.2–38.6 °C) suggests that the level of hyperthermia reached by our participants was probably not sufficient to alter neural drive (Thomas et al., 2005). Nevertheless, the delay between the cessation of exercise and the commencement of neuromuscular tests may also explain the absence of marked changes in neuromuscular performances following the cycling exercise (Froyd et al., 2013). The hypothetical occurrence of central alterations in HOT should therefore be considered at an individual level.

Table 1
Neuromuscular performances of knee extensors. Measurements performed before (PRE) and after (POST) the cycling exercise. MVC, maximal voluntary contraction (N); VAL, voluntary activation level (%); Tw_p, peak twitch (N); $Db_{10:100}$, ratio of 10-Hz doublet/100-Hz values. Data are presented as mean ± SE. [a] Significant intra-condition effect of cycling exercise (PRE > POST, $P < 0.05$).

	EXP_{TMP}		CON_{TMP}		EXP_{HOT}		CON_{HOT}	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST
MVC (N)	571 ± 103	561 ± 75	594 ± 96	555 ± 96[a]	569 ± 78	556 ± 101	588 ± 84	565 ± 71
VAL (%)	90.9 ± 6.4	89.1 ± 9.3	90.0 ± 5.5	88.4 ± 7.3	90.2 ± 5.4	88.4 ± 6.9	90.8 ± 5.7	86.9 ± 7.2[a]
M-wave (mV)	15.3 ± 5.4	15.3 ± 5.7	14.8 ± 4.5	15.6 ± 4.7	14.2 ± 4.3	14.1 ± 3.7	16.7 ± 5.3	17.0 ± 4.6
Twp (N)	168 ± 23	147 ± 30[a]	171 ± 22	147 ± 32[a]	167 ± 25	160 ± 30	175 ± 38	167 ± 33
$Db_{10:100}$	0.95 ± 0.10	0.85 ± 0.08[a]	0.96 ± 0.07	0.85 ± 0.10[a]	0.95 ± 0.09	0.89 ± 0.12[a]	0.90 ± 0.07	0.87 ± 0.07

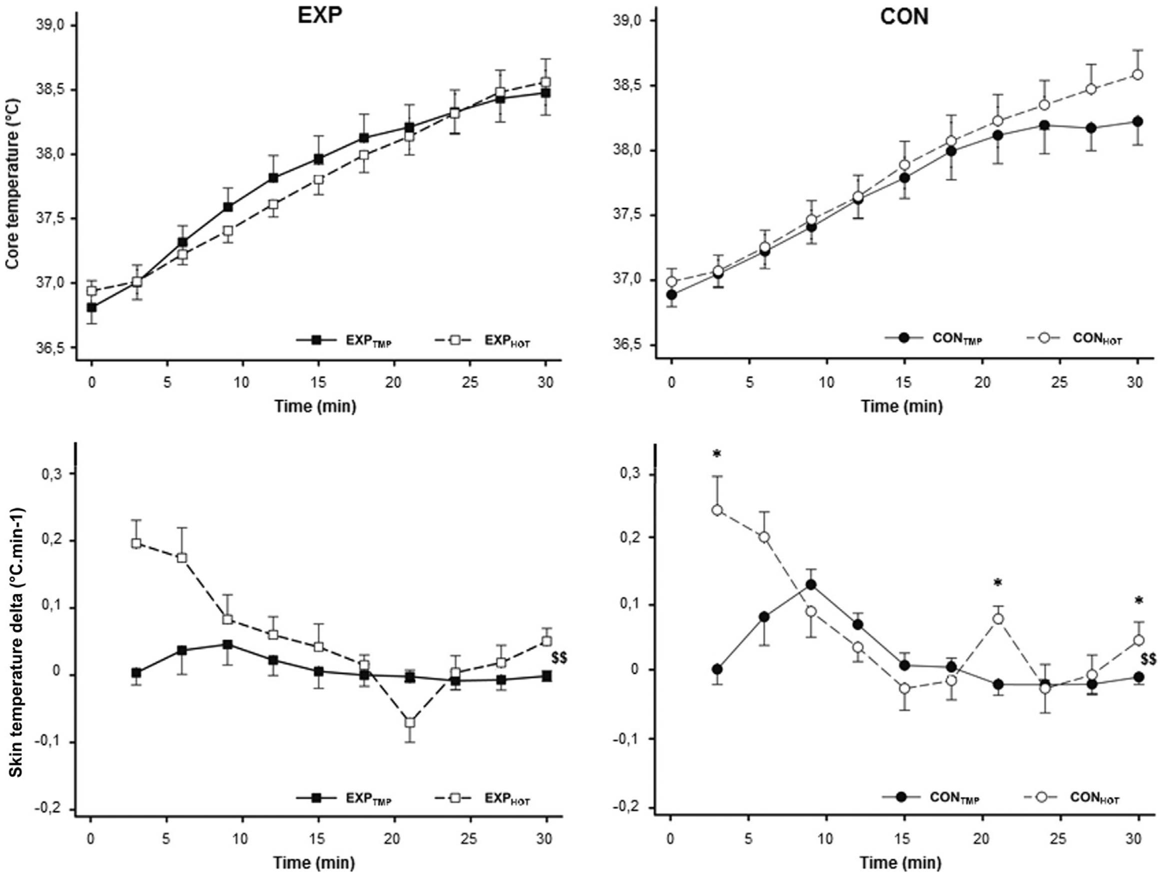

Fig. 5. Mean core (T_{CO}, upper part) and skin temperature (T_{SK}, lower part) variations throughout cycling exercise. Measurements following incongruent Stroop task (EXP, in the left) and passive control task (CON, in the right). Solid lines and black plots represent values assessed in neutral condition (TMP). Dotted lines and white plots represent values in hot condition (HOT). $^{\$\$}$Significant effect of ambient condition on mean variation (TMP < HOT, P < 0.05). *Significantly different from TMP ($P < 0.05$).

The physical responses (*i.e.* PO decline) were likely influenced by cardiovascular and perceptual changes as final effectors. The drift of HR recorded in HOT was in equal proportion to the reduction in PO. Changes in central command activation involved by the cardiovascular drift during prolonged exercise may induce a distortion of RPE (Norton et al., 1999). Furthermore, it cannot be excluded that cutaneous heat stimuli and subsequent thermal perception may have contributed to the regulation of PO at a fixed RPE (Schlader et al., 2011). Indeed our subjects did not perceive more discomfort in HOT than in TMP, although they reported through the NASA-TLX scale a higher effort produced in HOT which may reflect a higher cognitive demand. Although perceived exertion is now considered to be closely related to the activity of the central motor command (De Morree et al., 2012), afferent feedbacks initiated by physiological or sensory changes might challenge the complex affective and motivational processes which indirectly influence the perceived exertion (Craig, 2002; Venhorst et al., 2017). However, the current experimental protocol did not permit to dissociate the respective roles of perceptual and cardiovascular strain in the regulation of work rate in the heat.

Moreover, T_{CO} values recorded during the exercise in HOT indicate that hyperthermia was mild. In this context, previous manipulations of thermoregulatory inputs aiming to change T_{SK} (*i.e.* cold to hot *vs.* hot to cold) demonstrated similar increases in RPE, independently of subsequent variations of thermal perception (Hartley et al., 2012). Therefore, the inverse relation between T_{SK} and RPE, which has been supported following experimental protocols involving drastically different ambient conditions (Tucker et al., 2004), is valid only when the subject is free of physiological stress like during the initial stages of a self-paced exercise (Schlader et al., 2011). In this way, the perception of effort appears to be the key regulator of intensity when exercising in the heat (Flouris and Schlader, 2015) while the contribution of thermal perception probably fluctuates according to the hyperthermia level, but also to training experience. Increased thermal discomfort, which plays a major role in the decision to disengage from prolonged exercise, is largely influenced by T_{SK} and wetness in the condition of mild hyperthermia (Flouris and Schlader, 2015). However, endurance athletes that routinely face thermal disturbances are likely to implement, in this context, attentional strategies focused on environmental stimuli rather than somatic responses to increased skin blood flow or sweat rate (Schücker et al., 2009). This difference between perceived and physiological strain may probably explain their capacity to sustain greater T_{CO} values throughout self-paced exercise (Tikuisis et al., 2002). Therefore, previous experience and memorized sensations rather than emotional responses could affect, for this population, the self-regulation of exercise intensity (Brick et al., 2016).

5. Conclusion

Despite its challenging nature, the incongruent Stroop task had no effect on HR and sensation of fatigue in high level endurance athletes. This cognitive task was likely not stressful enough for endurance athletes given their high inhibitory control capacity. Therefore, cycling PO was not altered by the cognitive condition (EXP *vs.* CON) in both ambient conditions (TMP *vs.* HOT). These results do not allow to clarify on the combined effects of psychological and environmental stressors on the perception of effort. However, whatever the cognitive condition, the athletes started the exercise in HOT with a lower PO than in TMP and a faster rate of PO decline at fixed RPE was recorded throughout the exercise in HOT compared to TMP. The absence of higher post-exercise deterioration of muscle capacities suggests that perceptual responses and cardiovascular strain, both mediated through T_{SK}, played an important role in PO regulation in mild hyperthermia. When exercising in HOT, the distortion of RPE might be caused by physiological alterations (*i.e.* cardiovascular drift), and/or affective and motivational processes that heat sensations and subsequent discomfort involve. The absence of marked changes in the perception of discomfort in HOT for our participants might also support that training level influence the contribution of thermal perception on physical performance in the heat. Further studies are warranted to compare perceptual and emotional responses in highly trained and recreational athletes during self-paced prolonged exercise.

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Conflict of interest

The authors declare that they have no conflict of interest.

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