General article

Title: Heat acclimation training with intermittent and self-regulated intensity may be used as an alternative to traditional steady state and power-regulated intensity in endurance cyclists

Running title: Heat acclimation strategies for endurance athletes

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Abbreviations : ANOVA, analysis of variance; CI, confidence interval; ES, effect size; HA, heat acclimation; HA-HIGH, high intensity heat acclimation protocol; HA-LOW, low intensity heat acclimation protocol; Hb, haemoglobin; HCT, haematocrit; HR, heart rate; HR_{max}, maximal heart rate; HST, heat stress tolerance test; La, lactate; Na, sodium; PO, power output; PPO, peak power output; RPE, rate of perceived exertion; SWC, smallest worthwhile change; T_{CO}, core body temperature; T_{FA}, forehead skin temperature; T_{SK}, skin temperature; TT, cycling time trial

Abstract

The study aimed to determine the effects of self-regulated and variable intensities sustained during short-term heat acclimation training on cycling performance. Seventeen competitive-level male athletes performed a twenty-kilometre cycling time trial before (TT-PRE), immediately after (TT-POST1) and one week after (TT-POST2) a 5-day acclimation training program, including either RPE-regulated intermittent (HA-HIT, N=9) or fixed and low-intensity (HA-LOW, N=8) training sessions in the heat (39 °C; 40 % relative humidity). Total training volume was 23 % lower in HA-HIT compared to HA-LOW. Physiological responses were evaluated during a forty-minute fixed-RPE cycling exercise performed before (HST-PRE) and immediately after (HST-POST) heat acclimation. All participants in HA-LOW group tended to improve mean power output from TT-PRE to TT-POST1 (+8.1 ± 5.2 %; ES = 0.55 ± 0.23), as well as eight of the nine athletes in HA-HIT group (+4.3 ± 2.0 %; ES = 0.29 ± 0.31) without difference between groups, but TT-POST2 results showed that improvements were dissipated one week after. Similar improvements in thermal sensation and lower elevations of core temperature in HST-POST following HA-LOW and HA-HIT training protocols suggest that high intensity and RPE regulated bouts could be an efficient strategy for short term heat acclimation protocols, for example prior to the competition. Furthermore, the modest impact of lowered thermal sensation on cycling performance confirms that perceptual responses of acclimated athletes are dissociated from physiological stress when exercising in the heat.

Keywords: Cycling, Skin temperature, Core temperature, Rate of perceived exertion, Thermal perception.

Highlights

- The self-regulation of exercise intensity may substitute traditional fixed intensity
- An alternation of low and high intensities may be implemented in short-term heat acclimation
- Physiological rather than perceptual adaptation may dominate in short term heat acclimation

1. Introduction

An increasing number of sporting events will take place in hot and/or humid environments (e.g. 2021 Summer Olympics Games in Tokyo). It is well established that the effects of a high thermal load on cardiorespiratory and neuromuscular functions limit performance during prolonged exercise (Nybo et al. 2014). In this context, preparing for a major competition in the heat requires to implement specific training strategies such as heat acclimation (HA; Racinais et al. 2015). Although previous research has demonstrated the beneficial effects of HA for performance in the heat, through subsequent adaptations such as lowered core temperature (T_{CO}) and improved thermal comfort, conflicts between research-based recommendations and training priorities or schedules of well-trained endurance athletes must be considered (Casadio et al. 2017). Indeed, classical recommendations including prolonged training programs in the heat (i.e. at least 14 days) at low-to-moderate intensity (i.e. 50-60% VO_{2max}) are often not compatible with the athletes' training requirements (Périard et al. 2017). Moreover, given the rapid decay of heat adaptation (~2.5% per day when individuals are not exposed to the heat), and the limited opportunity for training between competitions in high-level endurance athletes, the search for innovative HA protocols combining repeated heat exposure with classical tapering/recovery strategies is warranted (Daanen et al. 2018; Mujika 2010).

In this context, short-term HA (i.e. less than 7 days) is emerging as a quicker alternative and thus more practical approach to classical HA protocols, with ongoing debate about its modalities of application (Sotiridis et al. 2020). Recent results suggest that as little as five 60-min exposures to heat (rectal temperature of 38.5°C) be sufficient to reduce physiological (i.e., heart rate, skin and rectal temperature) and perceptual (i.e., thermal sensation and comfort) strain during a subsequent exercise performed in the heat (Moss et al. 2020). Earlier results by Garrett et al. (2009; 2012) also showed beneficial effects of short-term HA (over 5 consecutive days), though exercise conditions (90-min exercise with rectal temperature ≥ 38.5°C in euhydrated or dehydrated state, respectively) are difficult to replicate in an ecological setting with athletes. Although the optimal duration of exposure to heat in short-term HA has been investigated and is still debated (the longest duration likely conferring the greatest adaptation to heat), the prescription of intensity of exercise sessions performed in the heat remains to be refined too. It can be hypothesized that intervals including competition-like intensities performed in a short-term HA protocol may increase the production of metabolic heat that could help to reach a sufficient thermal load in a shorter timeframe (Nevill et al. 1995; Sunderland et al. 2008; Wingfield et al. 2016). Such a strategy would therefore confer both the maintenance of the training stimulus that is required in the lead up to competitions, and the benefits of HA.

To the best of our knowledge, only one study investigated the application of competition-like intensities during a short-term HA training protocol (Schmit et al., 2018). In this study, the time to complete a 20-km cycling time trial (TT) increased following a high-intensity training strategy (+1.7 ± 1.3%), whereas it decreased following a low intensity training strategy (-2.2 ± 1.3%), after five days of HA (Schmit et al., 2018). The increase in TT completion time with the high intensity training strategy was explained, in most of the athletes, by overreaching symptoms such as increased subjective fatigue (Meeusen et al. 2013). As such, the modalities of intermittent HA training remain to be refined for maximal performance gains whilst limiting the risks of maladaptation. In this context, one emerging training option is to authorize the athletes to self-regulate training intensities according to their perceived exertion (Neal et al., 2016). Although the physiological adaptations derived from this strategy remain uncertain and a sufficient thermal load (i.e. increased core temperature) may not be reached, positive effects have been reported on affective processes (Parfitt et al. 2012). Moreover, such intermittent training sessions may amplify the optimization of thermal comfort that generally occurs following HA (Wingfield et al. 2016). Although thermal perception is considered as a mediating element of perceived exertion in the heat (Flouris and Schlader 2015), the influence of HA status on this interaction is not clearly established.

Within this framework, the primary aim of this study was to assess the immediate and delayed (i.e. post-1 week) effects of a short-duration intermittent HA training program on cycling endurance performance in the heat (i.e. 20-km time trial, TT). This original training strategy (HA-HIT) included intermittent bouts regulated according to the rate of perceived exertion (RPE), in a reduced total training volume of 270 min. It was compared to a reference training strategy (HA-LOW) including fixed-power and low-intensity bouts for a total training volume of 350-min. We hypothesised that both HA protocols would improve cycling performance, at least in equivalent proportions. The second aim was to compare the respective physiological and perceptual effects of both HA protocols during a standardized heat stress tolerance test (HST).

2. Material and methods

2.1. Participants

Seventeen competitive-level male athletes in cycling and triathlon (age: 35 ± 11 years; height: 1.78 ± 0.06 m; body weight: 72.9 ± 7.8 kg; peak power output: 4.6 ± 0.5 $W.kg^{-1}$) free from any metabolic, somatic or cardio-respiratory disorders were included in the entire study. They were classed in the performance level 3 or 4 according to guidelines for subject's classification in sports science research and usually trained, at least, 6h/week (De Pauw et al. 2013). All participants received no heat exposure (ambient temperature > 30 °C) in the 30 days prior to the study. All experimental procedures conformed to the Declaration of Helsinki and were approved by the local ethics committee of Université Côte d'Azur. All athletes received written instructions outlining all procedures and gave written informed consent.

2.2. Experimental design

The experimental design is presented in Fig. 1. The 6-week protocol aimed to investigate the effect of a 5-day HA training on cycling performance and subsequent physiological and perceptual responses recorded during *i)* a 20-km cycling time trial (TT) and *ii)* a submaximal and self-regulated cycling exercise called “Heat Stress Tolerance” test (HST). Athletes were randomly assigned to follow an experimental intermittent-intensity (HA-HIT; n = 9) or a reference low-intensity (HA-LOW; n = 8) HA protocol. Training sessions were all conducted during the winter season in South-East France (i.e. from December to March) at the same time of the day (± 2 hours).

During the inclusion visit, athletes completed a maximal cycling test to determine peak power output (PPO), following 6-min warm-up at 100 W and increments of 30 W per 2 min-stage until volitional exhaustion, using an electronically braked cycle ergometer (Schoeberer Rad Messtechnik, Jülich, Welldorf, Germany). Peak power output was calculated with the formula [$PPO = PO_{out} + (t/120) \times 30$] with PO_{out} (W) corresponding to the workload of the last completed stage and *t* (s) the time in the final stage.

All training sessions were performed on an air-braked cycle ergometer (Wattbike, Wattbike LTD, Nottingham, UK) disposed inside an environmental chamber. Ambient temperature and relative humidity (39 ± 1 °C; 40 ± 5 %) were continuously controlled with a probe positioned at the level of the athlete’s head in his riding position (Testo, Forbach, France).

All participants received written instructions to sleep for at least 7 hours, avoid strenuous exercise, drink a sufficient volume of water (i.e. 500 ml within the 2 hours prior to each session), limit consumption of caffeine, nicotine and alcohol for 24 hours and have the same diet for the two meals preceding each experimental session.

INSERT FIG. 1 HERE

2.3. Heat acclimation training

In week 4, all athletes completed a daily HA training session during five consecutive days (please refer to fig. 1 for more details about HA-LOW and HA-HIT training protocols). Both training protocols were designed in accordance with the methodology for short-term HA suggested by Chalmers et al. (2014) in their systematic review with meta-analysis on short-term HA strategies for improving physical performance.

Athletes included in the HA-LOW protocol exercised at fixed and submaximal intensities, individually determined from HST to reproduce alternately low (i.e. 33% PPO), moderate (i.e. 49% PPO) and high (i.e. 64% PPO) work rates during sessions, for a total training volume of 350 min. In the HA-HIT group, athletes were instructed to complete two series of ten 20-s intervals at a subjective "almost maximal" intensity (i.e. RPE-19) with a 1:2 recovery ratio (i.e. active recovery at a subjective "low" intensity – RPE-9), for a total training volume of 270 min. Individual training loads (i.e. TRIMP score) were calculated from the product of the training volume expressed in minutes and the training intensity expressed as absolute mean heart rate (HR) during session (Banister et al. 1975). The work completed (in kJ) per session was also deducted from power meter data and session durations.

2.4. Heat stress tolerance test

Exercise

A 40-min HST was performed before (HST-PRE) and immediately after (HST-POST1) the HA training period (Fig. 1). A familiarisation session applying the same protocol was performed during the first week of the experimental protocol. No forced wind exposure and no hydration were applied during trials.

During the first and the last 15 min, athletes were instructed to cycle at constant RPE intensities which gradually increased every 5 min (RPE-11, RPE-13 and RPE-15) [34].

Participants were allowed to freely adjust their cycling cadence and the resistance in order to maintain constant RPE intensities, whereas no feedback regarding time, distance covered, or PO was provided. All parameters were continuously recorded every 5 s during the entire duration of the test. The last minute of each 5 min fixed-RPE stage was retained to calculate the corresponding mean PO. A ratio was calculated from PO sustained during the two fixed-RPE stages performed at the same RPE level to describe the variation between them. Between the 15th and the 25th min of HST, athletes were instructed to cycle at a constant and fixed PO (50% PPO).

Measurements

Upon arrival at the laboratory, athletes estimated their level of fatigue, sleep quality and global muscle soreness using 0-7 points Likert scales.

Hydration status was then assessed through urine specific gravity (i.e. USG < 1.02). Sweat loss during exercise was calculated using the pre- and post-trial nude body mass quantified with a precision scale and corrected for fluids consumed. Given the experimental setup (i.e. protocol completed in a low-volume environmental chamber), a steady-state estimation of respiratory water losses from direct measurements was not possible.

Haematocrit level (HCT) was assessed from a 65-µl blood sample collected prior to the warm-up with heparinized capillary, using the I-STAT device (Abbott, Lake Bluff, IL) with an EC4+ compatible cartridge (Rudolf et al. 2015). Haemoglobin level (Hb) was derived from the HCT measurement [Hb = HCT × 0.34]. Both HCT and Hb values were used to estimate the pre to post HA expansion of plasma volume (Greenleaf et al. 1979).

Sweat samples were taken during exercises and analysed for sodium concentration. Before athletes entered the environmental chamber, sterile compresses were fixed on the lower part of both scapula by using dermal adhesive patches (10 × 10 cm, Tegaderm, HP, 3M®, Neuss, Germany). At the end of the HST, compresses were carefully separated from the adhesive tape using sterile tweezers before being inserted into the tube of a single-use syringe. Two 5-ml sweat samples were subsequently obtained by squeezing each wet compress into the syringe. Sweat samples were then stored at -18 °C in Eppendorff-type aliquots until analysis. Sodium concentration was then determined using an atomic absorption spectrometer (Spectraa 800, Verian, Palo Alto, CA). This measurement method was previously used in similar experimental studies (Harshman et al. 2018). Device calibration was performed using NaCl solutions (1000 ± 2 $\mu g.ml^{-1}$). Prior to analysis, sweat samples were diluted 1:10 in ultrapure water (MilliQ®, Millipore, Guyancourt, France).

Heart rate was monitored every 5 s by using a telemetric monitor (Garmin Pro, Garmin, Olathe, KA). Body temperature was monitored throughout the session. Core temperature (T_{CO}) 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 dedicated monitor (E-Celsius© Performance, Bodycap Medical). The capsule was ingested at the same time (± 1 hour) in a 6-12-hour window before each trial. Skin temperature (T_{SK}) 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) positioned on seven sites (forehead, left part of the chest, left forearm, right upper arm, left upper hand, right upper thigh and left calf) with surgical tape and bandage. Data were collected every 15 s through an acquisition system (DMM 2700, Keithley Instruments, Cleveland, OH) and averaged every 30 s. Mean T_{SK} was calculated according to a seven-site measurement model (ISO standard 9886, 2004). Forehead temperature (T_{FA}) was also assessed using a similar methodology. For these parameters, mean T_{SK} values recorded during the first two minutes of HST (START), the last two minutes of the 50% PPO HST (MID) and the last two minutes of HST (END) were retained for statistical analysis.

Thermal and comfort sensations were assessed using visual analogue scales at the first (START), 25th (MID) and 40th minute (END) of exercise. Athletes were instructed to respond to the question “How do you perceive the current thermal environment?” on a visual analogue scale ranging from -3 “very cold” to 3 “very hot” to determine thermal 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).

2.5. Time trial

Exercise

All participants completed four 20-km TT in hot/dry ambient conditions (same conditions as the training sessions): in the first week as a familiarisation (Schmit et al. 2016), prior (TT-PRE), immediately after (TT-POST1) and one week after the acclimation training (TT-POST2). Each TT was preceded by a 5 min rest period inside the environmental chamber and a standardised warm-up including 10-min at 100 W and 5-min at 50 % PPO. Participants were exposed to a forced ventilation and instructed to drink ad libitum during the entire trial. The volume of water ingested during TT-PRE was measured and replicated during the ensuing experimental sessions. No feedback was provided to the participants except for the distance remaining. Pacing analysis was performed over 0-2, 2-6, 6-10, 10-14, 14-18 and 18-20 km sections.

Measurements

Lactate concentration ([La^-]) was measured prior to the warm-up and at the end of the TT from a 5-µl capillary blood sample using a Lactate Pro System (LT-1710, Elitech, Puteaux, France).

Heart rate was continuously monitored during each TT. RPE, thermal sensation and comfort were also monitored from the 1st km and every 4 km thereafter until completion of the TT.

2.6. Statistical analysis

All data are presented as mean ± SD unless otherwise stated. Paired T-tests were used to compare mean intensities and total training loads between HA-HIT and HA-LOW. Two-way analyses of variance (ANOVA; "acclimation" × "training" condition; 2 × 2) were conducted to detect immediate (TT-POST1 *vs.* TT-PRE) or delayed (TT-POST2 *vs.* TT-PRE) effects of HA (HA-HIT *vs.* HA-LOW) on time, mean PO, physiological and perceptual parameters recorded during TT sessions. A two-way ANOVA ("acclimation" × "training" condition; 2 × 2) was also conducted for all parameters recorded during HST sessions. ANOVA for repeated measures ("acclimation" × "training" × "time" condition; 2 × 2 × 3) were also conducted with HR, T_{CO}, T_{SK}, T_{FA} and thermal perception values recorded for each HST (HST-POST1 vs HST-PRE) at START, MID and END time points. Pairwise comparisons using a Tukey's HSD were applied when a significant effect of acclimation or training was observed. For these statistical analyses, the significant level was set at a 95 % confidence level ($P < 0.05$). 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. T-tests and ANOVA were performed using Statistica software (Statistica version 8.0 for Windows, Statsoft, Tulsa, OK, USA).

Data recorded during TT (i.e. time, mean PO) were also analysed using a magnitude-based inference approach (Hopkins et al. 2009) to obtain more details about individual responses to HA training. The magnitude of the within-group changes (TT-PRE *vs.* TT-POST1 and TT-PRE *vs.* TT-POST2, for HA-HIT and HA-LOW separately), between-group differences in the changes (HA-HIT *vs.* HA-LOW in TT-PRE *vs.* TT-POST1 and TT-PRE *vs.* TT-POST2), and differences in the changes of group mean (HA-HIT *vs.* HA-LOW at TT-PRE, at TT-POST1 and at TT-POST2) that were induced by acclimation were calculated from this method. Magnitudes were interpreted by using effect sizes (ES) of 0.2, 0.6, 1.2, 2.0 and 4.0 of the variation as thresholds for small, moderate, large, very large, and extremely large differences in the change between the trials or groups. The smallest worthwhile change (SWC) was defined as 0.3 % and 0.7 % for TT's performance and mean PO, respectively (Paton and Hopkins 2006; Bonetti and Hopkins 2009). The practical interpretation of an effect was deemed unclear when *i)* ES value was less than 0.2 and *ii)* the 95% confidence interval (CI) of standardised change/difference included zero (Hopkins et al. 2009). Quantitative chances of higher or lower values than the SWC were evaluated qualitatively as follows: < 1 %, almost certainly not; 1 –5 %, very unlikely; 5–25 %, unlikely; 25–75 %, possible; 75–95 %, likely; 95–99 %, very likely; > 99 %, almost certain.

3. Results

3.1. Training load

All training session durations, mean session HR, and work done are reported in table 1. Although mean HR values (in %HRmax) were similar between groups and between training sessions ($P > 0.05$), the total training load (TRIMP score) sustained by the participants during HA was 26.3 % higher in HA-LOW compared to HA-HIT (HA-HIT *vs.* HA-LOW: 38105 ± 4003 *vs.* 51765 ± 3976 a.u.; $P < 0.001$). The work completed (in kJ) was also higher in HA-LOW compared to HA-HIT in session 3, 4 and 5 ($P < 0.001$). However, the total work done over the 5 training sessions was not different ($P = 0.27$) between HA-LOW (583.7 ± 63.0 kJ) and HA-HIT (528.0 ± 101.1 kJ).

Subjective measures of fatigue (*P* = 0.71; *ES* = 0.002) and sleep (*P* = 0.44; *ES* = 0.020) assessed before HST sessions were not affected by HA in both training groups.

3.2. Heat stress tolerance test

Power output

Heat acclimation had no effect on mean PO produced when participants sustained RPE-11, RPE-13 and RPE-15 efforts (*P* > 0.05). No difference was observed between the first and the second half of the test for each RPE stage of HST (*P* > 0.05).

Blood and sweat analysis

Although pre-training HCT values were significantly higher in HA-HIT compared to HA-LOW (*P* = 0.017; *ES* = 0.175), HA had no effect in both groups (*P* = 0.34; *ES* = 0.031; table 2). Post-training plasma volume increase in HA-HIT (+1.6 ± 13.1 %) and decrease in HA-LOW (-8.0 ± 16.0 %) were not significant (*P* = 0.20). Likewise, sweat losses (*P* = 0.64; *ES* = 0.008) and sodium concentration (*P* = 0.13; *ES* = 0.081) were not affected by HA in both groups, although a pre-post training decrease of [Na^+] was observed in 13 of the 17 participants.

Heart rate and body temperature

Heart rate recorded during HST (table 2) was not different between groups at any time point, nor was different between HST-PRE and HST-POST1 (*P* = 0.23; *ES* = 0.049).

T_{CO} values measured before the start of HST were not different between groups, nor was affected by HA (*P* = 0.68; *ES* = 0.06). During HST, the increase in T_{CO} was lower after HA (*P* = 0.007; *ES* = 0.216) without difference between HA-HIT and HA-LOW (table 2).

HA had a significant effect on the T_{SK} variation during HST (Fig. 2), with differences between training groups (POST1 *vs.* PRE; HA-HIT vs. HA-LOW: $P = 0.024$; $ES = 0.129$). The post-hoc analysis showed that these differences occurred during the second half of HST (MID *vs.* END) while T_{SK} increased significantly during the first half in all testing conditions (START *vs.* MID: $P < 0.05$). In HA-HIT, the T_{SK} increase during HST became significant after HA (POST1; START *vs.* END: 35.6 ± 0.9 *vs.* 36.2 ± 0.7 °C; $P = 0.018$). Conversely in HA-LOW, the increase in T_{SK} was significant before HA (PRE; START *vs.* END: 37.2 ± 0.3 *vs.* 38.6 ± 0.6 °C; $P < 0.001$) but not after (POST1; START *vs.* END: 37.1 ± 0.4 *vs.* 38.2 ± 0.6 °C; $P = 0.31$).

HA also significantly affected the T_{FA} variation with differences between training groups (POST1 *vs.* PRE; HA-HIT *vs.* HA-LOW; $P = 0.029$; $ES = 0.123$). In HA-HIT, the T_{FA} decrease was similar before and after HA (PRE and POST1; END > START; $P < 0.05$). In HA-LOW, this same T_{FA} decrease occurred after HA only (POST1; END > START; $P < 0.05$).

Perceptual values

The variation of thermal sensation during HST was significantly altered by HA in similar proportion between groups ($P = 0.007$; $ES = 0.169$). In HST-PRE, values increased gradually from start to the end of exercise (END *vs.* START: in HA-HIT, 2.4 ± 0.7 *vs.* 1.2 ± 1.0 a.u.; in HA-LOW, 2.6 ± 0.5 *vs.* 1.5 ± 0.8 a.u.) conversely to HST-POST1 (END *vs.* START: in HA-HIT, 1.5 ± 1.0 *vs.* 1.3 ± 0.9 a.u.; in HA-LOW, 1.6 ± 1.2 *vs.* 1.7 ± 0.5 a.u.). Perceived thermal comfort decreased throughout HST-PRE and HST-POST sessions but was not affected by HA ($P = 0.28$; $ES = 0.042$).

3.3. Time trial

Completion time

There was no immediate (TT-POST1 *vs.* TT-PRE: $P = 0.28$; $ES = 0.04$) or delayed (TT-POST2 *vs.* TT-PRE: $P = 0.72$; $ES < 0.01$) effect of HA on TT completion time (Fig. 3).

Between-group differences were unclear at baseline. Within-group changes revealed a likely small decrease in TT completion time in the HA-LOW group (-2.8 ± 1.6 %; $ES = -0.44 \pm 0.18$) but unclear effects in the HA-HIT group (-1.2 ± 2.4 %; $ES = -0.22 \pm 0.26$). Performance was improved in TT-POST1 for 6 of the 9 HA-HIT athletes (-23 ± 44 s), and for all the athletes in HA-LOW (-52 ± 30 s). The delayed effects of HA (*i.e.* in TT-POST2) were unclear in both groups (-0.1 ± 3.5 % and -1.5 ± 3.4 %; $ES = 0.03 \pm 0.39$ and -0.32 ± 0.54, in HA-HIT and HA-LOW, respectively).

INSERT FIG. 2 HERE

Power output

The study of mean PO during TT did not show any immediate (TT-POST1 *vs.* TT-PRE: $P = 0.18$; $ES = 0.06$) or delayed (TT-POST2 *vs.* TT-PRE: $P = 0.57$; $ES = 0.01$) effect of HA on PO (Fig. 3).

Inference calculations revealed unclear between-group differences at baseline. Within-group changes showed a likely small increase of PO for the HA-LOW group (+8.1 ± 5.2 %; $ES = 0.55 \pm 0.23$) and unclear effects for the HA-HIT group (+4.3 ± 2.0 %; $ES = 0.29 \pm 0.31$). Mean PO sustained in HA-HIT was 69.4 ± 5.3 %, 72.3 ± 6.9 % and 69.5 ± 6.8 % PPO in TT-PRE, TT-POST1 and TT-POST2, respectively. In HA-LOW, athletes sustained 66.8 ± 5.5 %, 72.2 ± 5.4 and 70.4 ± 6.9 % of PPO in TT-PRE, TT-POST1 and TT-POST2, respectively.

With regards to the pacing strategy (Fig. 4), mean PO sustained during the first two kilometres of TT-PRE was likely moderately higher in HA-HIT than in HA-LOW (+5,6%; $0.2 < ES < 0.6$), whereas between-group differences were unclear in TT-POST1 and in TT-POST2.

Within-group changes from TT-PRE to TT-POST1 were unclear in HA-HIT. In HA-LOW, there was a likely moderate increase in PO sustained from 0 to 2 km (+9.9 ± 2.0 %; *ES* = 0.70 ± 0.29), and 2 to 6 km (+10.1 ± 2.9 %; *ES* = 0.72 ± 0.40). Then the PO increase became possibly to likely small from 6 to 20 km (0.2 < *ES* < 0.6). Within-group changes between TT-PRE and TT-POST 2 were unclear at baseline in both groups.

Physiological responses

In both groups, blood lactate concentration measured before TT was not different ($P > 0.05$). Blood lactate concentration increased during all TT sessions ($P < 0.05$) with no immediate (TT-POST1 *vs.* TT-PRE: $P = 0.063$; *ES* = 0.11) or delayed (TT-POST2 *vs.* TT-PRE: $P = 0.95$) effect of HA on post-exercise values.

Mean and maximal HR values during TT were not affected by HA, both immediately after (TT-POST1 *vs.* TT-PRE: $P = 0.75$ and $P = 0.78$, respectively) and one week later (TT-POST2 *vs.* TT-PRE: $P = 0.62$ and $P = 0.48$, respectively).

INSERT FIG. 3 HERE

Perceptual values

There was no immediate (TT-POST1 *vs.* TT-PRE) or delayed (TT-POST2 *vs.* TT-PRE) effect of HA on RPE values recorded during TT ($P > 0.05$). Likewise, mean values of thermal perception (i.e. thermal sensation and comfort) were not different between TT-POST1 and TT-POST, and between TT-POST2 and TT-PRE ($P > 0.05$).

INSERT FIG. 4 HERE

4. Discussion

The purpose of this study was to examine the immediate and delayed effects of an original 5-day HA protocol including intermittent bouts (HA-HIT) *vs.* a classical low-intensity HA strategy (HA-LOW) on cycling endurance performance of well-trained athletes. The novelty of our original short-term HA protocol was in the regulation of exercise intensity according to RPE in HA-HIT, in a lower training volume (i.e. -23%) than HA-LOW. Both HA strategies tended to improve 20-km TT performance with mean PO increases of 4.3 ± 2.0 % and 8.1 ± 5.2 % in HA-HIT and HA-LOW, respectively, though these differences were not significant. Both HA strategies conferred a lower body thermal gain during exercise, though in lower proportion compared to longer HA protocols as reported in the literature. Furthermore, the similar PO regulation despite lower thermal sensation in HST-POST for both groups, suggests that perceptual responses of acclimated athletes are dissociated from physiological stress when exercising in the heat. Beyond the likely improved endurance performance level, the absence of post-HA overreaching symptoms in HA-HIT suggests that perceptually self-regulated work rate may limit the risk of maladaptation to HA training and may be considered as a viable training option in the close proximity to competition in the heat. However, the lack of marked physiological adaptations contrary to previous studies using fixed or isothermal intensities, suggests that RPE-regulated intensities during short-term HA may lower the thermal stress that is required for heat adaptation.

4.1. Effect of HA strategies on endurance performance

The current literature suggests multiple strategies to improve endurance performance of well-trained athletes in hot environment. Among them, pre-competitive short-term (i.e. 5 consecutive days) HA seems to be the most adapted to athletes' training and competitive schedules (Chalmers et al. 2014; Gibson et al. 2015; Moss et al. 2020). Although previous studies have investigated the respective effects of different thermal loads in short-term HA (Houmard et al., 1990; Wingfield et al. 2016; Gibson et al. 2015; Moss et al. 2020), the incidence of the intermittent production of competition-like intensities in the heat remains unknown. Only a recent study highlighted that the performance delivered by well-trained athletes on a 20-km cycling TT was strongly impaired immediately after a short-term HA including competition-like intensities, conversely to another group who trained at low intensity in the same hot conditions (Schmit et al. 2018).

With this in mind, we hypothesised that the self-regulation of high intensities during intermittent training sessions performed in the heat could mitigate the risks of maladaptation. Hence, for the first time we asked one group of athletes (HA-HIT) to regulate low and very high exercise intensities in the heat according to their RPE *vs.* a classical heat training protocol (HA-LOW) where exercise intensity was regulated via power output. We observed that all athletes in HA-LOW increased their mean PO after HA (in a range of 0.1-18.6 %, NS, *ES* = 0.55), while only one of the nine athletes of HA-HIT group sustained a lower mean PO (-8.6 %, NS, *ES* = 0.29). The average magnitude of PO increase that we recorded for HA-LOW is in the same order as that described by Schmit et al. (2018), who reported a 6.7 ± 4.6 % increase in their fixed low-intensity group after the first week of HA. Conversely, our results in HA-HIT contradict those of Schmit et al. (2018) who observed a 4.9 % decrease in mean PO following a high-intensity HA protocol involving almost similar total heat exposure time compared to our protocol (300 *vs.* 270 min in Schmit et al. (2018) vs. ours, respectively). Another observation from our study was that performance gains observed in TT-POST1 were not maintained in TT-POST2, regardless of the training group. A 5-day HA period is generally sufficient to generate stable cardiovascular and thermoregulatory adaptations that can persist beyond the training period (Chalmers et al. 2014). In our study, it can be hypothesised that heat acclimation decay (i.e. generally -2.5 % for each day without heat exposure) might have been exacerbated, in both training groups, by the short total duration of heat exposure, thus reducing performance in TT-POST2 (Daanen et al. 2018).

The analysis of the pacing strategy during TT revealed a similar pattern to the study of Schmit et al. (2018), both in HA-LOW and HA-HIT. In TT-POST1, our participants presented a higher PO during the first 6-km of the TT (TT-POST1 vs. TT-PRE: +11.5 ± 5.5 % and +10.0 ± 6.6 % in HA-HIT and HA-LOW, respectively). This faster start in TT-POST1 resulted in a better final performance for 14 participants. This change in pacing strategy in TT-POST1 was surprising considering that our well-trained participants shifted to a slower start from TT familiarisation to TT-PRE. Besides, the completion of endurance events in the heat is often associated, in trained athletes and regardless of acclimation status, with a reduced starting PO (Racinais et al. 2015). Such pacing adjustments are generally explained by anticipatory mechanisms that aim to maintain a physiological threshold below which exercise can be optimally sustained until completion (Marino 2004). In accordance with the psychobiological model of endurance performance (Pageaux 2014), it cannot be excluded that improvements in thermal perception may have contributed to a greater starting PO (Sunderland et al. 2008). Conversely, the analysis of RPE variations during TT does not support the hypothesis of a more aggressive pacing strategy after HA.

From the 6th to the 18th kilometre of the TT, we observed that the relative stability in PO (i.e. from 1 to 2 % of decrease) was not affected by HA status, and HR was similar in TT-PRE and TT-POST1. Moreover, the statistical trend in favour of higher post-exercise [La-] suggests that athletes produced a higher muscular work throughout TT-POST1 though post-HA metabolic adaptations remain uncertain. At last, similar RPE values were recorded during the last kilometre of each TT (18.9 ± 1.3, 19.0 ± 1.4 and 18.4 ± 1.5 in TT-PRE, TT-POST1 and TT-POST2, respectively) highlighting the fact that participants systematically reached their maximal level of perceived exertion at the end of the TT.

4.2. Physiological and perceptual responses to HA strategies

The efficacy of any HA strategy is evaluated against the amplitude of performance enhancement and associated cardiovascular, thermoregulatory, and/or perceptual changes (Sawka et al. 2011). While meaningful adaptations can occur in well-trained athletes following a short-term HA training (Racinais et al. 2015; Schmit et al. 2018), it is however established that longer periods of HA are more appropriate for optimising physiological responses during exercise in hot ambient conditions (Daanen et al. 2018). Considering that post-HA performance gains disappeared in TT-POST2, we can suggest that most of our athletes responded positively to 5-day HA training, but the effects remained for a short period of time only. For instance, similar mean HR values were recorded in TT-PRE and TT-POST1 while mean PO tended to be higher in the latter. Lower post-HA cardiovascular stress is associated with a slight expansion of plasma volume which usually occurs after 3 to 4 consecutive days of heat exposure (Sawka and Coyle 1999). However, in our study plasma volume was unchanged after HA suggesting other mechanisms, such as a lower body temperature, to explain the lower cardiovascular stress (Gonzalez-Alonso et al. 1999).

Roberts et al. (1977) argued that autonomic mechanisms of human thermoregulation are primarily mediated by changes in body temperature. Whilst basal values were unchanged after HA, the continuous measurement during HST showed a lower increase in T_{CO} in both training groups while PO values were similar. The lower thermal gain observed during exercise would primarily be explained by a greater metabolic efficiency and subsequent lower production of endogenous heat by the working muscles (Marino 2015; Rivas et al. 2017). However, overall T_{SK} and T_{FA} values recorded during the second half of HST-POST were higher in HA-HIT than in HA-LOW. This result suggests that post-HA adaptations of blood transfers from the deep body tissues to the skin were different between HA-HIT and HA-LOW (Sawka et al. 2011). It cannot be excluded that a lower temperature threshold for the onset of sweating or cutaneous vasodilation in HST-POST initiated a similar heat loss compared to HST-PRE, despite a reduced production of metabolic heat (Fujii et al. 2012). Furthermore, it is also possible that 13 of the 17 participants with a lower sweat [Na+] concentration in HST-POST, compared to HST-PRE, sustained a lower thermal gain due to a facilitation of evaporative cooling (Buono et al. 2018).

Perceptual responses to the activation of central and peripheral thermal sensors may also play a major role in the self-regulation of exercise intensity in the heat (Schlader et al. 2011a). Whilst pre- and post-HA perceptual responses assessed during TT were similar, lower thermal sensations during the second half of HST-POST1 confirm that five consecutive days of heat exposure could be sufficient to induce changes in thermal responses. Moreover, similar perceptual adaptations observed in both groups despite a shorter exposure time in HA-HIT confirm that high-intensity training in the heat may help alleviate more effectively heat sensation and subsequent discomfort during exercise (Sunderland et al. 2008; Wingfield et al. 2016). The lower thermal sensation recorded in HST-POST1 could be attributed to physiological adaptations such as reduced thermal load and increased heat dissipation (Yao et al. 2007). In this way, variations in T_{SK} and T_{FA} could be viewed as surprising while T_{FA} is considered as a primary modulator of thermal perception during exercise (Malgoyre et al. 2018). We hypothesise that our athletes became less sensitive to increases in ambient temperature following HA (Mäkinen et al. 2004). The current dissociation between thermal sensation and T_{SK}, as previously shown during a fixed-RPE exercise (Schlader et al. 2011b), suggests that HA separates perceptual from physiological adaptations during physical exercise. Accordingly, using external strategies to improve perceptual cues before competition (i.e. pre-cooling) probably confers a less powerful effect on endurance performance in acclimated well-trained athletes (Schmit et al. 2018).

4.3. Practical implications and limitations

The aim of this study was to examine the potential of a short HA training strategy that could be used as a substitute to longer and less practical HA training strategies during a precompetitive period. Although HA-LOW strategy tended to induce greater improvements in TT performance (differences were not significant), results obtained with HA-HIT suggest that intermittent training bouts in the heat may be implemented a few days prior to a prolonged self-paced event. As tapering is usually applied within days prior to competition (Mujika 2010), incorporating short high-intensity training sessions in the heat would be adapted as athletes and practitioners are bound by time and logistical constraints between competitions. On another hand, we cannot exclude that repeated daily heat exposure during high-intensity sessions may cause an unplanned rise in internal training load due to the accumulation of repeated daily HA sessions (Crowcroft et al. 2015). Moreover, although a minimal session duration of 30 min has been reported for HA in team sports (Sunderland et al. 2008), current recommendations prescribe at least 60 min of daily heat exposure to improve endurance performance in hot environment (Chalmers et al. 2014). Despite our positive results in terms of adaptation to training (no sign of maladaptation to training was reported), the current reduction of training volume (-23 %) should however be regarded. Future studies should investigate how a greater decrease of training volume – from 40 to 60% as usually implemented during taper (Bosquet et al. 2007) – may influence the HA process in ecological training conditions in well-trained endurance athletes.

In addition to the reduction in training volume, the perceptual self-regulation of intensity as applied in our study likely played a role in the mitigation of maladaptation to HA-HIT. Positive affective responses to self-regulated training might counteract the psychological effects of an intense session, particularly in hot environment (Bresciani et al. 2011). The self-regulation of exercise intensity is compatible with usual training programs of well-trained endurance athletes such as intermittent sessions (Ciolac et al. 2015), all the more as the greater emotional ability of well-trained athletes to subjectively tolerate extreme physiological stress (i.e. RPE-15 and above) might contribute to sustain high PO values during short intervals (Bixby and Lochbaum 2006). However, there is still no consensus on how self-regulated training sessions might impact short- and long-term endurance performance. From that perspective, the analysis of daily training load showed that HA-HIT group presented higher variability in the mean intensity sustained (HA-HIT vs. HA-LOW: 58-87 *vs.* 69-86 % HR_{max} in day 1, 60-83 *vs.* 71-81 % HR_{max} in day 5), and the work done (in kJ) was lower in session 3, 4 and 5 in HA-HIT compared to HA-LOW. Hence, we cannot exclude that the thermal load was not sufficient to confer consistent physiological and perceptual heat adaptation, for some participants. At last, a supplementary control group that did not perform HA training would be necessary to identify the specific HA effects and pacing adjustments during TT in the heat.

5. Conclusions

The current data highlight that intermittent exercise bouts including competition-like intensities during short-term HA training may induce similar positive effects on physical performance in the heat compared to a classical HA training strategy, when intensity is self-regulated from RPE. Short-term subsequent physiological adaptations, rather than changes in post-HA perceptual responses, might explain the improved performance level in acclimated athletes. Our results, showing no negative effect on training adaptation in the heat, suggest that self-regulated intermittent-intensity HA strategy may be considered as a viable alternative to classical fixed, low intensity and longer HA protocols, generally applied within days prior to sporting events in the heat. However, in our study, the lack of marked physiological adaptation to HA as classically reported in previous studies using fixed or isothermal intensities, suggests that the thermal load was likely not sufficient for some participants. This study must be considered as a first stage in the implementation of RPE regulated short-term HA protocols for athletes, and additional studies are required to determine the optimal combination between reduced exercise duration and increased intensity to confer a sufficient thermal stress for heat adaptation.

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Author contributions

GR, TB, PF and JL were involved in the conception and design of the experiment. GR, TB and PF completed data collection and data analysis. GR, TB, PF and JL interpreted the data and wrote the initial manuscript. All authors revised the manuscript and approved the final submission.

Declaration of interest

The authors declare no conflicts of interest.

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Tables

Table 1 Duration (expressed in minutes), intensity (mean heart rate expressed in percentage of the maximal heat rate), and work done (in kJ) over the five training sessions, in HA-HIT and HA-LOW. Data are presented as mean ± SD

	HA-HIT			**HA-LOW**		
	Duration	**Intensity**	**Work done**	**Duration**	**Intensity**	**Work done**
Session 1	70	72.0 ± 9.6	581.1 ± 134.9	70	77.1 ± 7.6	653.6 ± 143.9
Session 2	50	78.8 ± 8.9	709.4 ± 203.6	70	82.4 ± 5.3	663.5 ± 143.3
Session 3	50	75.4 ± 6.5	447.8 ± 63.4*	70	77.1 ± 5.9	665.4 ± 144.3
Session 4	50	77.7 ± 4.2	474.1 ± 74.7*	70	80.1 ± 4.1	711.7 ± 153.2
Session 5	50	71.0 ± 7.7	399.8 ± 107.1*	70	76.6 ± 3.9	654.2 ± 150.8

Table 2 Physiological parameters measured throughout HST-PRE and HST-POST1. Data are presented as mean ± SD. START: mean value during the first two minutes of trial; MID: mean value during the last two minutes of the 50% PPO stage; END: mean value during the last two minutes of trial. [Na+], sweat sodium concentration * *Significant effect of heat acclimation (PRE < POST, $p < 0.05$)*

	HA-HIT		**HA-LOW**	
	HST-PRE	**HST-POST1**	**HST-PRE**	**HST-POST1**
Heart rate (beats.min^{-1})				
START	108 ± 14	98 ± 17	117 ± 25	108 ± 17
MID	146 ± 13	141 ± 11	149 ± 17	150 ± 15
END	164 ± 15	160 ± 17	169 ± 21	168 ± 20
Core temperature (°C)	36.9 ± 0.2	37.0 ± 0.3	37.1 ± 0.3	37.0 ± 0.4
Thermal gain (°C)	1.5 ± 0.4	1.0 ± 0.3*	1.5 ± 0.4	1.1 ± 0.4*
Sweat loss (kg)	2.2 ± 0.7	2.0 ± 0.7	1.9 ± 0.4	1.9 ± 0.8
Sweat [Na$^+$] (mg.l^{-1})	1603 ± 292	1367 ± 515	1574 ± 583	1268 ± 494
Haematocrit rate (%)	47 ± 3	50 ± 4	46 ± 4	45 ± 3

Figures

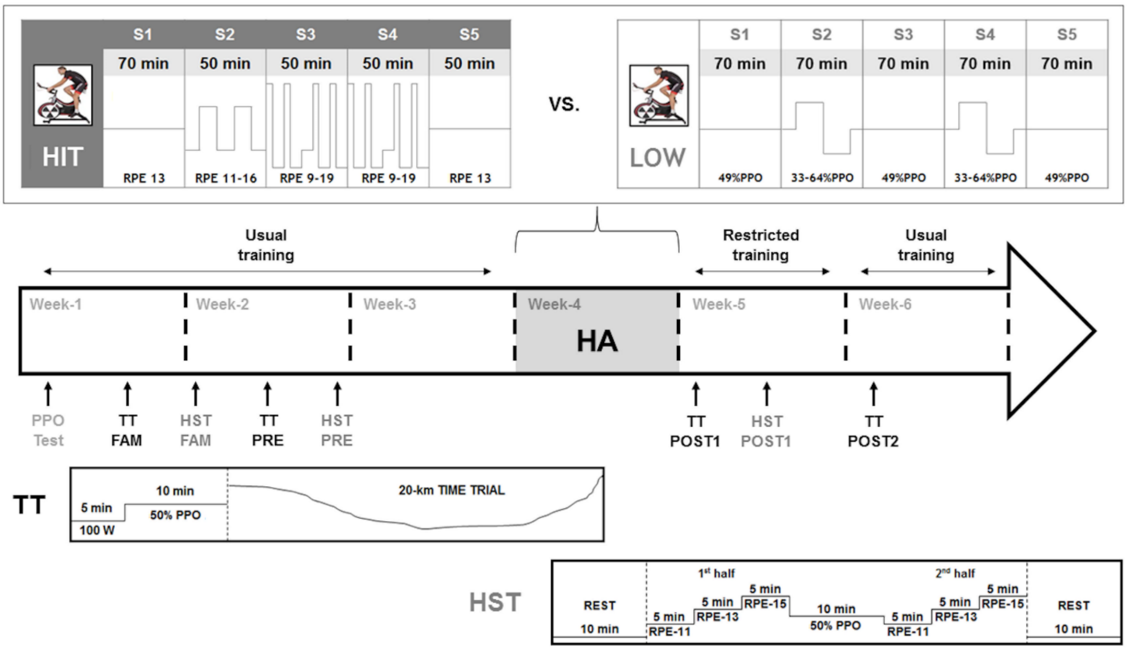
HIT
S1
S2
S3
S4
S5
70 min
50 min
50 min
50 min
50 min
RPE 13
RPE 11-16
RPE 9-19
RPE 9-19
RPE 13
VS.
LOW
S1
S2
S3
S4
S5
70 min
70 min
70 min
70 min
70 min
49%PPO
33-64%PPO
49%PPO
33-64%PPO
49%PPO
Usual training
Restricted training
Usual training
Week-1
Week-2
Week-3
Week-4
HA
Week-5
Week-6
PPO Test
TT FAM
HST FAM
TT PRE
HST PRE
TT POST1
HST POST1
TT POST2
TT
5 min
100 W
10 min
50% PPO
20-km TIME TRIAL
HST
REST
10 min
1st half
5 min
RPE-11
5 min
RPE-13
5 min
RPE-15
10 min
50% PPO
2nd half
5 min
RPE-11
5 min
RPE-13
5 min
RPE-15
REST
10 min

Fig. 1 Overview of the experimental design. HIT: "experimental" training group, RPE-regulated and variable intensity. LOW: fixed power-regulated intensity; TT: 20-km time trial; HST: heat stress tolerance test sustained at a fixed RPE; FAM: familiarisation session to the time trial; HA: heat acclimation protocol; PPO: peak of power output

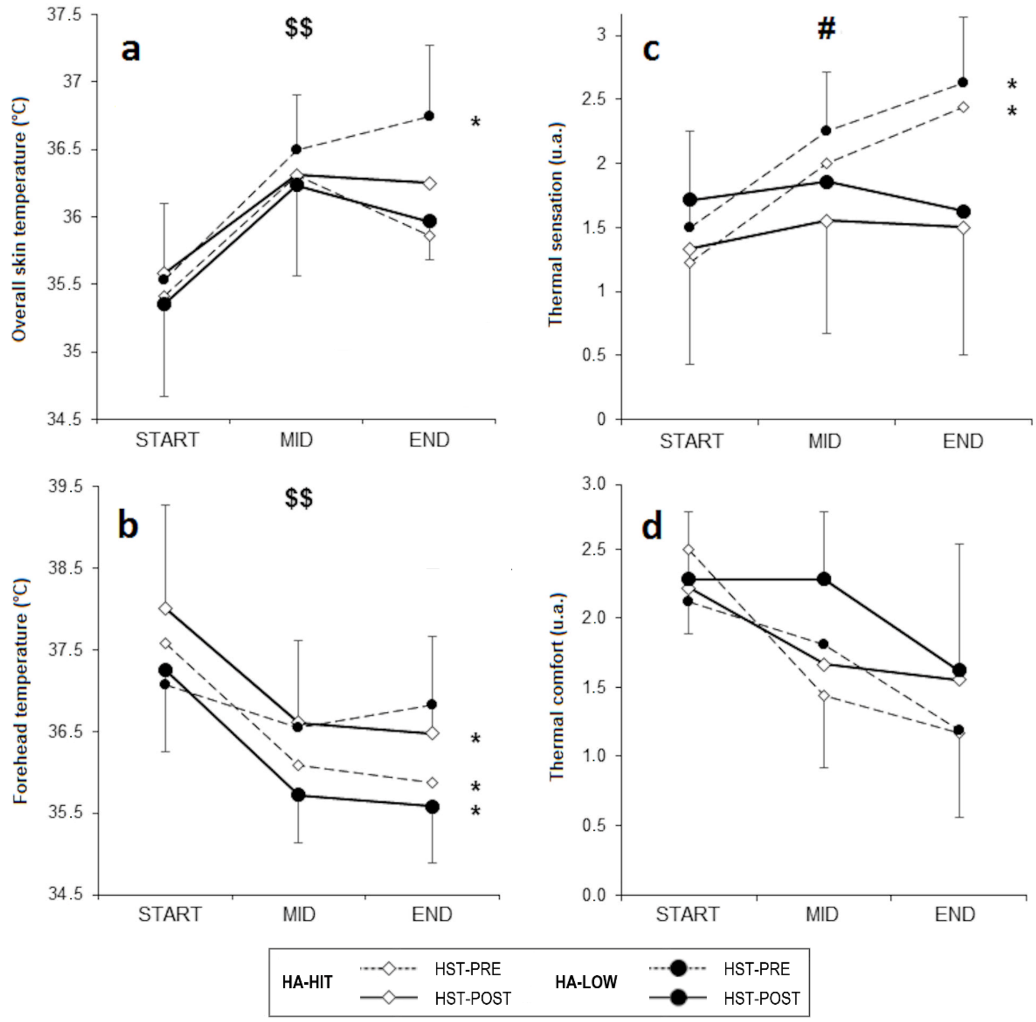

Fig. 2 Skin temperature (a), forehead temperature (b), thermal sensation (c) and thermal comfort (d) at the start (START), the middle (MID) and the end (END) of HST-PRE (thin and dotted line) and HST-POST (bold and solid line). Black dots represent values recorded in the fixed-intensity group (HA-LOW). White lozenges represent values recorded in the experimental high-intensity group (HA-HIT) * Significant difference between the start and the

end of the trial (END vs. START, $p < 0.05$). # Significant within group difference of variation observed both in HA-HIT and HA-LOW (HST-POST vs. HST-PRE, $p < 0.05$). $$ Significant difference in respective variations observed in HA-HIT and HA-LOW (HST-POST vs. HST-PRE, $p < 0.05$)

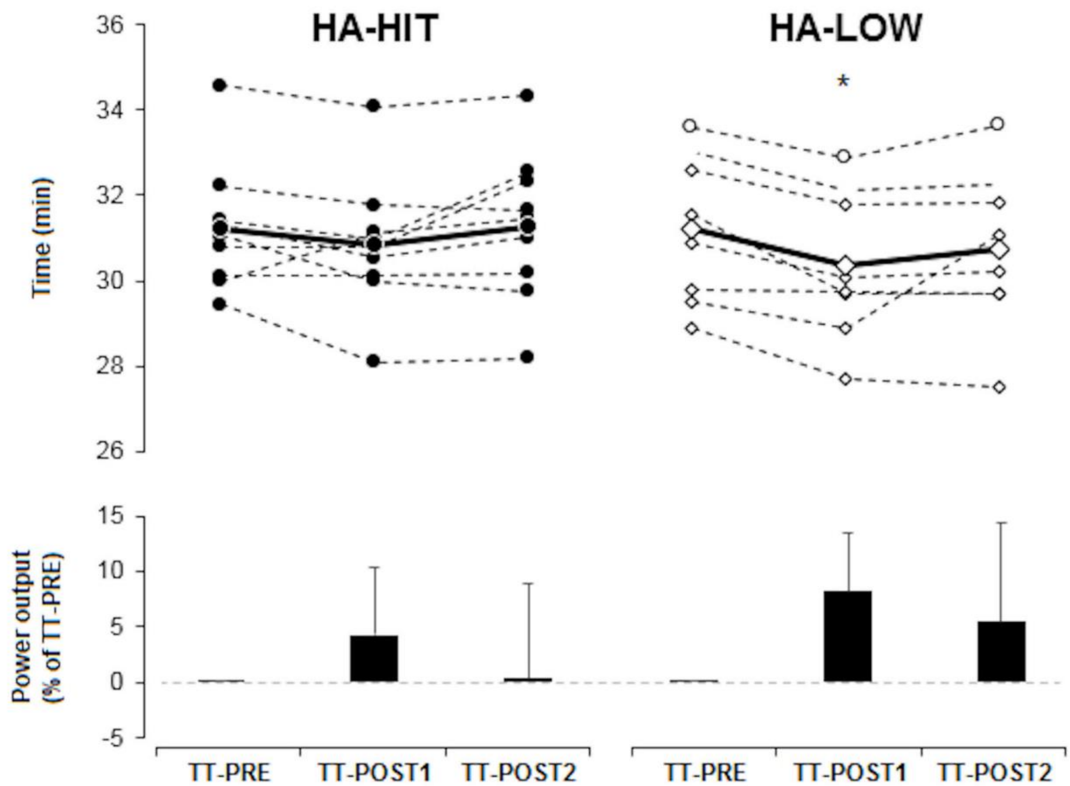

Fig. 3 Individual (dotted lines), mean (bold lines) time-trial durations and corresponding relative changes in mean power output for each group assessed before (TT-PRE), 2-3 days after (TT-POST 1) and 8-10 days (TT-POST 2) after heat acclimation # Very likely small decrease from TT-PRE (-0.2 > ES > -0.6)

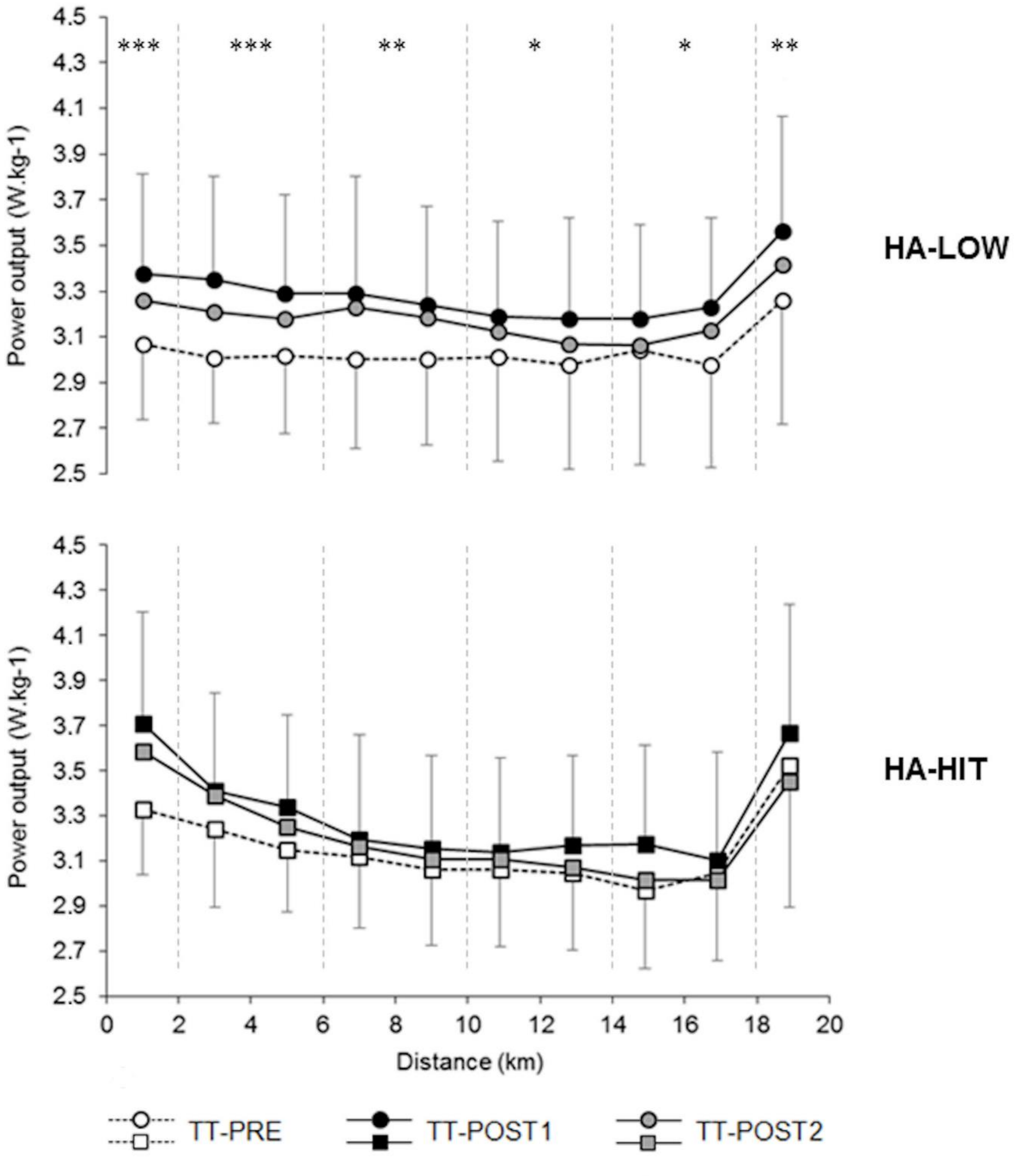

Fig. 4 Mean power output per 2-km stage for each group during TT-PRE (dotted line and white dots), TT-POST 1 (solid line and black dots) and TT-POST 2 (solid line and grey dots) * Likely small increase compared to TT-PRE (0.2 < ES < 0.6). ** Very likely small increase compared to TT-PRE (0.2 < ES < 0.6). *** Very likely moderate increase compared to TT-PRE (0.6 < ES < 1.2)