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SPECIAL ISSUE PAPER

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Cognitive function during self-paced cycling under heat stress: Performance, perceptual, and neuromuscular fatigue responses in athletes

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ABSTRACT

Heat stress impairs both physical and cognitive function, yet its impact on simultaneous cognitive-motor dual-tasking (CMDT) remains unclear. Sixteen trained athletes completed two high-intensity CMDT sessions in hot (HOT, 40°C) or temperate (CON, 20°C) conditions. Each 21-min cycling exercise comprised 7-min at a self-paced 'strong' intensity followed by 14 min at a fixed-power, based on the last power selected, during which participants performed two 7-min blocks (Ex7-14, Ex14-21) of a sustained attention task (SART). Heart rate (%HR_{max}), rectal temperature (T_{rec}), and perceived mental effort were monitored, while knee-extensor neuromuscular fatigue was assessed after exercise via femoral nerve stimulation during a 1-min sustained maximal contraction. Self-paced power output was lower in HOT (198 ± 49 W) than CON (223 ± 46 W, P <0.001). %HR_{max} rose more steeply in HOT (interaction P <0.001), whereas T_{rec} did not differ between conditions (38.5 ± 0.4°C at Ex21). SART performance declined over time (−10 ± 7%, P = 0.006) but was consistently lower in HOT (64 ± 12%) vs. CON (74 ± 8%, P = 0.004), despite similar increases in perceived effort. The force loss during sustained contraction was greater in HOT (−71 ± 21%) vs. CON (−54 ± 19%, P = 0.024). Despite lower self-paced power, heat stress further impaired concurrent cognitive performance during CMDT and subsequent force production, indicating greater fatigue development.

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Cognitive-motor dual-task; exercise; temperature; attention; femoral stimulation

Introduction

Physical activity is often combined with concurrent specific and impactful cognitive demands such as memory, attention, or executive functioning, forming cognitive-motor dual-task (CMDT) situations (Woollacott & Shumway-Cook, 2002). These situations are increasingly observed in clinical rehabilitation, but also in major sporting competitions and occupational activities (e.g., military, firefighting) that often occur in challenging environmental conditions (e.g., heat stress), where performance and health can be compromised (Al-Yahya et al., 2011). CMDT requires co-regulation of physical and cognitive components to avoid interference (Pashler, 1994), yet performance depends on both human/internal resources (e.g., fitness level, familiarisation) and task/external demands (e.g., complexity, duration, environmental stressors) (Sudo et al., 2022).

In the context of climate change, understanding CMDT under heat stress is increasingly important, as exposure to high temperatures is becoming more frequent and intense (Seneviratne et al., 2023). Heat exposure negatively affects both physical (Périard et al., 2021) and cognitive (Taylor et al., 2016) performance. Heat stress exacerbates cardiovascular strain in part through extensive cutaneous vasodilation, and during exercise this translates into higher perceived effort and reduced mechanical power output, even when core temperature rises similarly to temperate conditions (Périard et al., 2021; Tatterson et al., 2000).

Leading models propose inverted-U relationships between core temperature or exercise intensity and cognitive performance, suggesting optimal cognition at ~38.5°C or moderate exercise intensities, likely due to arousal and neurotransmitter release (Lambourne & Tomporowski, 2010; McMorris et al., 2016; Schmit et al., 2017). However, these theories are debated: simple cognitive tasks appear unaffected by passive heating, whereas complex tasks show impairments, with functional MRI revealing altered brain activity despite similar core temperatures (~38.5°C) during the tasks (Liu et al.,

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2013). Thus, both exercise intensity and heat-induced hyperthermia can be considered strong mediators of cognitive functioning, raising the question of whether simultaneously demanding physical exercise further impairs cognition.

Both cognitive (Banich et al., 2000) and physical tasks (Li et al., 2014) recruit cerebral regions that can overlap. Heat stress can alter brain functioning via hypovolemia, impairing complex cognitive tasks (Wittbrodt et al., 2018), but it remains unknown how superimposed exercise interacts with cognition under heat. A unique study suggests executive functioning and memory decline during CMDT after heat exposure (Schlader et al., 2022), yet these involved postural tasks or post-exercise assessments, limiting generalisation to whole-body exercise such as cycling.

Neuromuscular fatigue, defined as a decline in isometric maximal voluntary contraction (IMVC), arises from both central and peripheral mechanisms (Bigland-Ritchie et al., 1986). Heat preferentially affects central mechanisms by reducing maximal voluntary activation (Racinais & Oksa, 2010). Yet, in situations involving reduced power output in the heat, such as perceived self-paced cycling (Roussey et al., 2018) or prolonged cycling trials (Périard et al., 2011), central fatigue is not exacerbated, suggesting that lower mechanical output may counterbalance adverse thermal effects. CMDT itself may increase central fatigue by taxing shared brain resources (Goepp et al., 2024), but this interaction under heat remains unexplored.

The present study aimed to investigate CMDT performance, including perceived self-paced cycling, attentional performance, and neuromuscular fatigue, in hot and temperate environments in trained participants. We hypothesised that heat would exacerbate neuromuscular fatigue and impair attentional performance, driven by a higher degree of hyperthermia compared with temperate conditions.

Materials and methods

Participants

A total sample of 16 participants (2 females/14 males) were recruited (age: 34 ± 10 yrs; body mass: 75 ± 12 kg; body mass index: 23.6 ± 3.2 kg·m^{-2}, weekly sport: 8.4 ± 2.9 h). All the participants were trained/developmental (Tier 2) in the Participant Classification Framework (McKay et al., 2022) and the main sports identified were triathlon, cycling and running. The participants refrained from intense or unhabitual physical exercise for 24 h and from consuming caffeine for 6 h before the experimental sessions. The study followed the principles of the Declaration of Helsinki (2008 edition) and was approved by the institutional ethics committee (University of Brighton, 2024–14446). All participants provided written informed consent prior to the study and were naive to the study aims and hypotheses.

Sample size estimation and justification

No formal *a priori* sample size calculation was performed due to resource constraints, specifically the absence of comparable experimental designs and a restricted timeframe to complete all experimental sessions (Lakens, 2022). Based on sample sizes previously used in similar exercise paradigms under heat stress (i.e., self-paced cycling, n = 11–12 participants) (Roussey et al., 2018; Tatterson et al., 2000), we sought to recruit 16 participants. A sensitivity test *a posteriori* was performed, according to GPower 3.1 software calculation, indicating that the current sample size was sufficient to consistently detect large effect sizes of f = 0.47 (i.e., η_p^2 = 0.18), with a power of 95%, for the within interaction of a repeated-measures ANOVA design.

Experimental design

Participants completed one familiarisation session followed by two experimental sessions, allowing evaluation of CMDT performance and neuromuscular function in either a hot or a temperate environment. Due to logistical constraints, all participants completed the hot session first, followed by the temperate session, with approximately two months between sessions. To minimise potential order effects, the familiarisation session was carefully structured to standardise task execution, and participants' training load was monitored during the four weeks preceding each experimental session, revealing no significant changes in training habits or baseline thermophysiological variables. Baseline values for all sessions are reported in Supplementary Material 1.

1st visit: Familiarisation and incremental cycling test

The first visit was conducted to familiarise the participants with cycling at various levels of perceived effort using the 100-points Borg scale (CR_{100}) (Borg et al., 2020), determine preferential cadence, as well as with the procedures for neuromuscular function assessment. The participants also completed the Sustained Attention to Response time Task (SART, cf. *Cognitive performance* section) at rest (1 × 60 trials) and while cycling (1 × 120 trials). Then, the participants performed an incremental cycling test to determine maximal heart rate (HR_{max}, 182 ± 12 bpm) and peak power output (PPO, 331 ± 58 W). The first stage started at 140 W, with work-rate being increased by 15 W every minute until volitional exhaustion despite verbal encouragement. PPO was determined as the last 1-min completed stage.

2nd and 3rd visits: Hot and temperate trials

After a baseline evaluation of the right knee-extensor neuromuscular function (cf. *Force assessment and femoral nerve stimulations*), participants were involved in a 12-min progressive warm-up (4 × 3 min at respectively 13-easy, 23-moderate, 50-strong and 23-moderate intensity, respectively on the CR_{100}). Then, the participants entered the thermal chamber (TISS, Hampshire, UK) which was set as temperate (CON, 20°C/40%) or hot (HOT, 40°C/40% humidity). They completed a cycling exercise lasting 21 min and divided into 3 × 7-min blocks: firstly 7 min of self-paced cycling (Ex0-7) at a constant intensity corresponding to an effort perceived as 50-strong on the CR_{100} and after, 2 × 7 min at a fixed cycling intensity based on the final power selected by the participant during Ex0-7 (Ex7-14, Ex14-21). Self-paced exercise was chosen to individualise cycling intensity (Haile et al., 2015), as most previous studies tested heat stress using fixed parameters (e.g., 30-min running at 9 km·h^{-1}, 2% slope), which often led to earlier exhaustion (Mee et al., 2015). Previous work reported that 4 min was sufficient to stabilise self-paced power in temperate conditions (Goepp et al., 2024). Based on pilot testing and additional thermal strain, we extended this period to 7 min in the hot environment to ensure stable and representative self-paced power. The participants were asked to maintain their preferential cadence throughout the cycling task (85.3 ± 6.2 RPM), with visual feedback. Importantly, the participants performed the SART task during Ex7-14 and Ex14-21 (i.e., CMDT). No fluid was consumed during the whole session. Upon completion of CMDT trials, participants exited the chamber and underwent a neuromuscular function assessment including a 1-min sustained IMVC. This procedure allowed us to limit misinterpretation of voluntary activation reduction due to the delay (~30 s between exiting the chamber and initiating the knee-extensors contraction, as previously used (Périard et al., 2011). An overview of the experimental design is presented in Figure 1.

Measurements

Hydration

On arrival to the laboratory, participants voided their bladder to provide a urine sample for each session. Euhydration, permitting continuation of the protocol was confirmed when the following criteria were achieved: a urine osmolality of ≤ 700 mOsm·kg^{-1} H_2O (Pocket Pal-Osmo, Vitech Scientific, Ltd) and gravity value of ≤1.020 (hand refractometer, Atago Co., Tokyo, Japan). If participants did not meet the hydration criteria, they were provided with a 500 mL bolus of water. Values are presented in Supplemental Material 1.

Cycling power

Cycling trials were conducted on a stationary cycle ergometer (Wattbike Ltd, Nottingham, UK) with self-regulated airflow resistance, adjusted by participants via a manually operated flap mechanism. The coefficient of variation for the Wattbike has been previously reported as 2.6% (Mcgrath et al., 2019). Power output was averaged over each 7-min block (Ex0-7, Ex7-14 and Ex14-21) and expressed as a percentage of PPO (%PPO).

Heart rate and core temperature

A single use rectal temperature (T_{rec}) probe (449 H, Henleys Medical, Hertfordshire, UK) was self-inserted by

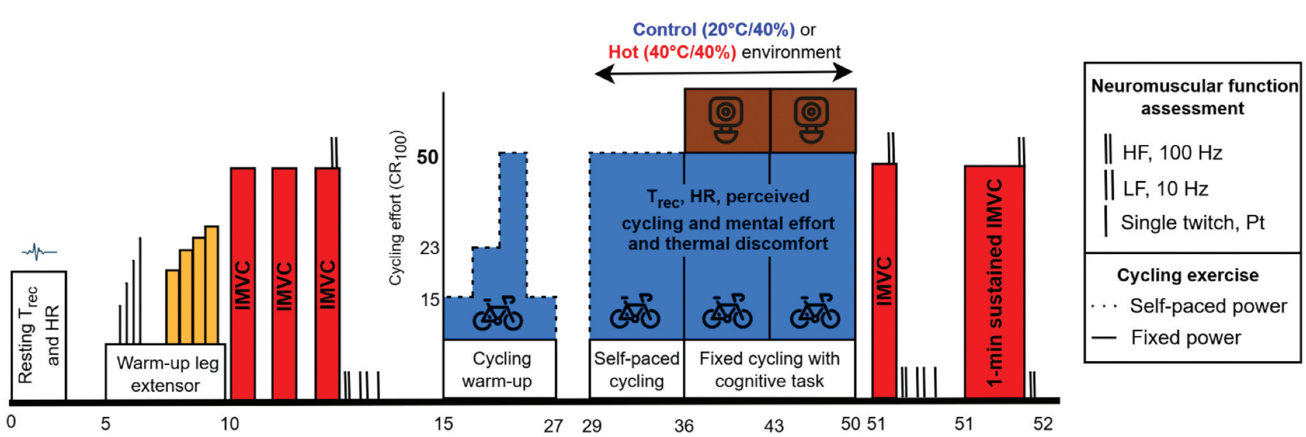

Figure 1. Overview of the experimental session including the cycling combined with the SART task. HF: high-frequency doublet. HR: heart rate. IMVC: isometric maximal voluntary contraction. LF: low-frequency doublet. Pt: peak twitch. T_{rec}: rectal temperature.

the participants 10 cm past the anal sphincter. Data were displayed on logging monitors (YSI, 4600 series, YSI, Hampshire, UK) to provide T_{rec} as single values at Ex0, Ex7, Ex14 and Ex21. A Polar H10 heart rate monitor (Polar electro, Kempele, Finland) was also fitted as a chest strap. HR was averaged over the 7-min blocks in the chamber (Ex0-7, Ex7-14 and Ex14-21), and expressed as $\%HR_{max}$.

Sweating responses

Changes in body mass (Adam GFK 150 Body Scales, Connecticut, USA, accurate to 0.01 kg) was calculated in each experimental trial using the following formula:

$$Sweat\ rate\left(L \cdot h^{-1}\right) = \left(\frac{(BM_{PRE} - BM_{POST})}{Exercise\ time}\right) * 60$$

where BM_{PRE} and BM_{POST} are respectively dry nude body masses before and after the 21-min cycling exercise.

Cognitive performance

The SART was employed to evaluate sustained attention during cycling trials, using web-based resource PsyToolkit (version 3.6.0) (Stoet, 2017). The task involved a random display of numbers from 1 to 9 on a computer screen, for a duration of 250 ms for each iteration, interspaced with a response window of 800 ms. Participants were instructed to click on a connected mouse on the bicycle handlebars, as quickly as possible for all numbers, except for the number 3, for which they had to withhold their response (11% of all trials). Participants were instructed to prioritise both speed and accuracy to mitigate potential trade-offs between these variables. Reaction time, accuracy, and a composite score that equally weighed these two factors were systematically evaluated. Each block lasted ~6 min 30 s (320 trials) and the three performance indicators were averaged across blocks. Prior to data collection, participants were provided with a comprehensive description of the task and its instructions. At the beginning of the experimental session, participants completed a brief practice block of 30 trials to remind themselves of the task mechanics.

Sustained attention was selected to expand existing knowledge in a cognitive domain that remains underexplored compared to executive functions (McMorris & Hale, 2012), despite its high relevance in operational and athletic settings (Blacker et al., 2019; Habay et al., 2021). Additionally, as prior research indicates that sustained attention is impaired during high-intensity exercise in temperate environments (Goepp et al., 2024, 2025), we sought to investigate its potential interaction with heat-induced physiological strain.

Force assessment and femoral nerve stimulations

To assess peripheral and central indices of neuromuscular fatigue, electrical stimulations were administered percutaneously to the femoral nerve via a cathode electrode (10-mm diameter; Meditrace 100, Covidien) placed on the inguinal triangle. A rectangular anode electrode (50 × 90-mm, Durastick Plus, DJO Global, Vista, CA, USA) was attached to the gluteal fold. An electrically induced square wave of 1-ms duration was delivered using a constant current stimulator (DS7A, Digitimer, Welwyn Garden City, Hertfordshire, UK). Outside the chamber, at the beginning of each session, to determine the optimal intensity of stimulation, single stimuli were delivered incrementally in steps of 10 mA, every 5 s, until the twitch amplitudes plateaued. The optimal intensity was then increased by 20% for subsequent evaluations to ensure supramaximality. Following the warm-up including increased isometric knee-extensions, the evaluation started with a 3-s IMVC with one high-frequency doublet (HF, 100 Hz) evoked during the force plateau. Three electrical stimuli were then delivered to the relaxed muscle interspersed with 3 s between each stimulus: one Db_{100}, one low-frequency doublet (LF, 10 Hz), and one singlet (peak twitch, Pt). This evaluation was repeated ∼30 s after the cycling trials outside the chamber ($POST_{EX}$) and followed by a 1-min sustained IMVC. Maximal force was averaged over the first and last 5 s of this sustained contraction ($IMVC_0$ and $IMVC_{60}$). A superimposed HF stimulus was applied at 55 s during the sustained IMVC and again immediately after relaxation. The low-frequency to high-frequency ratio (LF/HF) was used as an index of low-frequency fatigue (Verges et al., 2009), and VA was calculated as a central fatigue indicator using the formula (Strojnik & Komi, 1998):

$$VA(\%) = \left(1 - \frac{SIT * \frac{F_{init}}{IMVC}}{HF}\right) * 100$$

where SIT is the amplitude evoked when HF was delivered on IMVC, F_{init} is the force before the stimulation, HF is the amplitude on relaxed muscle.

Perceived cycling and mental effort and thermal discomfort

Cycling effort, asked as 'What is the difficulty of your cycling exercise?' (Marcora, 2010) and mental effort asked as 'What is the mental effort associated with the situation?' (Marcora et al., 2009) were assessed using the

CR_{100}. Thermal discomfort was assessed using the question 'How hot do you feel right now?' on a 10-cm visual analogue scale ranging from 0 ('neutral') to 10 ('unbearably hot'). All measurements were assessed at the end of each 7-min cycling block.

Statistical analysis

All statistical analyses were performed using JASP software (version 16, Amsterdam, The Netherlands) and statistical significance was set at $P < 0.05$. Data are presented as mean ± SD. Shapiro Wilk tests were conducted to assess the normal distribution of the data. In cases where sphericity was violated (Mauchly), Greenhouse-Geisser corrections were applied. To examine the effects of heat on SART performance, two-way *time* × *condition* analysis of variance for repeated measures (ANOVAs RMs) were performed on the two CMDT blocks (Ex7-14 and Ex14-21) across conditions (CON, HOT). For cycling power, HR and perceived responses, the same two-way *time* × *condition* ANOVAs RMs were performed while adding Ex0-7 (cycling alone) in *time* factor whereas T_{rec} was analysed at Ex0, Ex7, Ex14 and Ex21. Other two-way *time* × *condition* ANOVAs RMs were conducted on IMVC, VA, LF/HF and Pt before and after cycling trials (baseline, $POST_{EX}$) across conditions (CON, HOT), and for the 1-min sustained IMVC at $IMVC_0$ and $IMVC_{60}$ (*time* factor). One-way *condition* ANOVAs RMs were dedicated to sweat rate data and VA_{IMVC60} (i.e., assessed at the end of the 1-min sustained contraction). Pairwise Bonferroni procedures were applied for post-hoc analyses when ANOVA revealed significant results. The partial eta squared (η_p^2) for ANOVA analysis was calculated, where $\eta_p^2 < 0.01$ indicates a very small effect, $0.01 \le \eta_p^2 < 0.06$ a small effect, $0.06 \le \eta_p^2 < 0.14$ a moderate effect, and $\eta_p^2 \ge 0.14$ a large effect (Cohen, 2013).

Results

Power and physiological responses

For self-paced power, a main effect of *condition* ($F_{(1, 15)} = 29$, $P < 0.001$, $\eta_p^2 = 0.66$) was reported (Figure 2A) with no *time* effect ($P = 0.63$) or *condition* × *time* interaction ($P = 0.12$). Power was higher ($P < 0.001$) in CON (67 ± 5%PPO, ~223 ± 46 W) compared to HOT (59 ± 7% PPO, ~198 ± 49 W). For T_{rec}, a main effect of *time* ($F_{(3, 45)} = 183$, $P < 0.001$, $\eta_p^2 = 0.92$) was reported (Figure 2B) with no *condition* effect ($P = 0.58$) or *condition* × *time* interaction ($P = 0.062$). T_{rec} increased linearly (from 37.7 ± 0.3°C at Ex0 to 38.4 ± 0.4°C at Ex21, all $P < 0.001$). For HR, a main effect of *time* ($F_{(2, 30)} = 134$, $P < 0.001$, $\eta_p^2 = 0.90$) and *condition* × *time* interaction ($F_{(2, 30)} = 15$, $P = 0.001$, $\eta_p^2 = 0.50$) were reported (Figure 2C) with no *condition* effect ($P = 0.073$). HR increased between Ex0-7 and Ex7-14 (+14 ± 5 bpm, $P < 0.001$) and between Ex7-14 and Ex14-21 (+4 ± 3 bpm, $P < 0.001$) and tended to be higher ($P = 0.095$) in HOT at Ex14-21 (94 ± 4%HR_{max}) compared to CON (89 ± 6%HR_{max}). No main effect of *condition* ($P = 0.84$) was observed for sweat rate with comparable values in HOT (1.4 ± 0.4 $L{\cdot}h^{-1}$) and CON (1.4 ±0.5 $L{\cdot}h^{-1}$).

Cognitive performance

For SART score, a main effect of *condition* ($F_{(1, 15)} = 31$, $P < 0.001$, $\eta_p^2 = 0.68$) and *time* ($F_{(1, 15)} = 11$, $P = 0.004$, $\eta_p^2 = 0.43$) were reported (Figure 3A) with no *condition* × *time* interaction ($P = 0.35$). SART score decreased between Ex7-14 and Ex14-21 (−5.8 ± 3.6%, $P = 0.004$) and was lower in HOT compared to CON (−10.8 ± 4.2%, $P < 0.001$). For SART accuracy, main effect of *condition* ($F_{(1, 15)} = 29$, $P < 0.001$, $\eta_p^2 = 0.66$) and *time* ($F_{(1, 15)} = 10$, $P = 0.006$, $\eta_p^2 = 0.40$) were reported (Figure 3B) with no *condition* × *time* interaction ($P = 0.27$). SART score decreased between Ex7-14 and Ex14-21 (−10.3 ± 6.7%, $P = 0.006$) and was lower in HOT compared to CON (−20.7 ± 10.6, $P < 0.001$). For SART reaction time, no *condition* ($P = 0.38$), *time* effect ($P = 0.18$) or *condition* × *time* interaction ($P = 0.77$) were reported (Figure 3C).

Neuromuscular function

For IMVC, a main effect of *time* ($F_{(1, 15)} = 38$, $P < 0.001$, $\eta_p^2 = 0.73$) was reported (Figure 4A) with no *condition* effect ($P = 0.64$) or *condition* × *time* interaction ($P = 0.68$). IMVC decreased between baseline and $POST_{EX}$ (−12.6 ± 9.1%, $P < 0.001$). For Pt, a main effect of *time* ($F_{(1, 15)} = 23$, $P < 0.001$, $\eta_p^2 = 0.62$) was reported (Figure 4B) with no *condition* effect ($P = 0.35$) or *condition* × *time* interaction ($P = 0.52$). Pt decreased between baseline and $POST_{EX}$ (−12.3 ± 9.5%, $P < 0.001$). For LF/HF, a main effect of *time* ($F_{(1, 15)} = 22$, $P < 0.001$, $\eta_p^2 = 0.61$) was reported (Figure 4C) with no *condition* effect ($P = 0.36$) or *condition* × *time* interaction ($P = 0.49$). LF/HF decreased between baseline and $POST_{EX}$ (−18.7 ± 8.9%, $P < 0.001$). For VA, a main effect of *time* ($F_{(1, 15)} = 28$, $P < 0.001$, $\eta_p^2 = 0.67$) was reported (Figure 4D) with no *condition* effect ($P = 0.44$) or *condition* × *time* interaction ($P = 0.61$). VA decreased between baseline and $POST_{EX}$ (−5.5 ± 2.6%, $P < 0.001$). During the 1-min sustained IMVC, a main effect of *time* ($F_{(1, 15)} = 85$, $P < 0.001$, $\eta_p^2 = 0.87$) and *condition* × *time* interaction ($F_{(1, 15)} = 13$, $P = 0.003$, $\eta_p^2 = 0.49$) were reported (Figure 5A) with no *condition* effect ($P = 0.15$). IMVC was lower in HOT compared to CON at

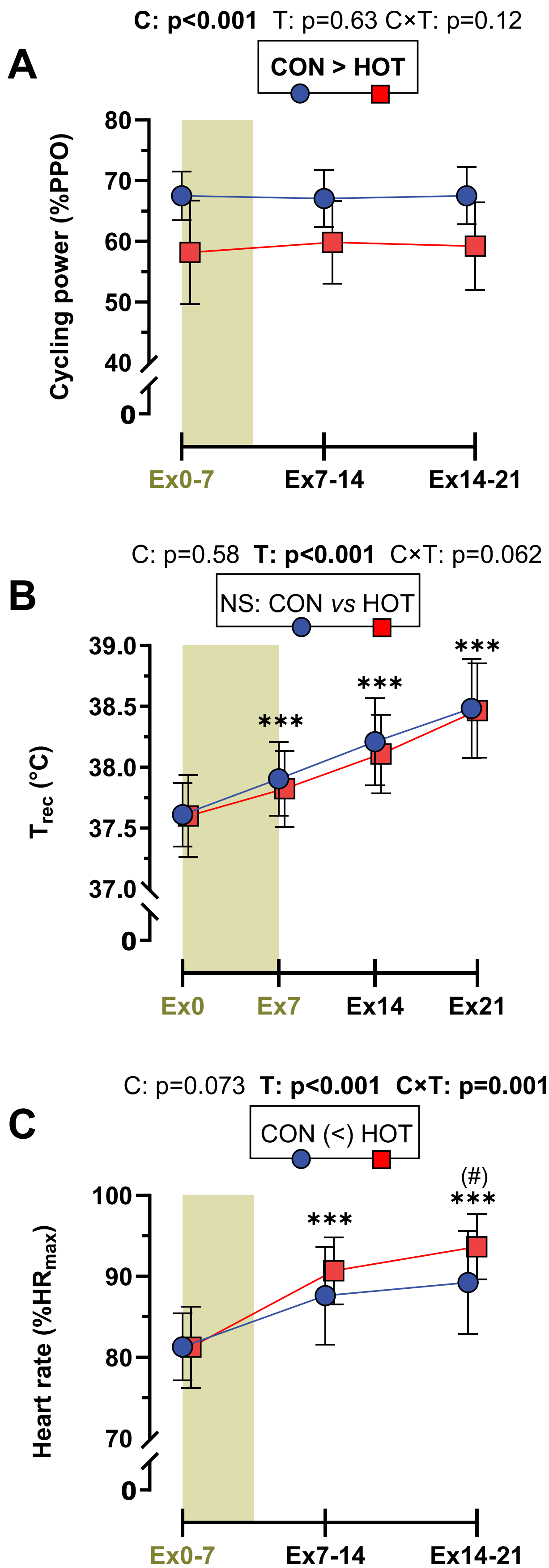

Figure 2. Cycling power in % of peak power output (%PPO, panel A), rectal temperature (T_{rec}, panel B), and heart rate in percentage of maximal heart rate (%HR_{max}, panel C) during self-paced cycling (brown area, Ex0-7) followed by fixed-power cycling with the SART task (Ex7-14, Ex14-21) in hot (HOT) or temperate (CON) environment for N = 16. Data are presented as mean ± standard deviation. Boxed text presents the *group* effect and p-values for main effects of *condition* (C), *Time* (T) and *condition* × *Time* (C × T) are displayed above each panel. Post-hoc significant differences for *Time* effect are marked with the following symbols: ***: P-value <0.001 vs. respective previous time-point. For *condition* × *Time* interaction are marked with the following symbols: (#): P-value = 0.095 between conditions at Ex14-21.

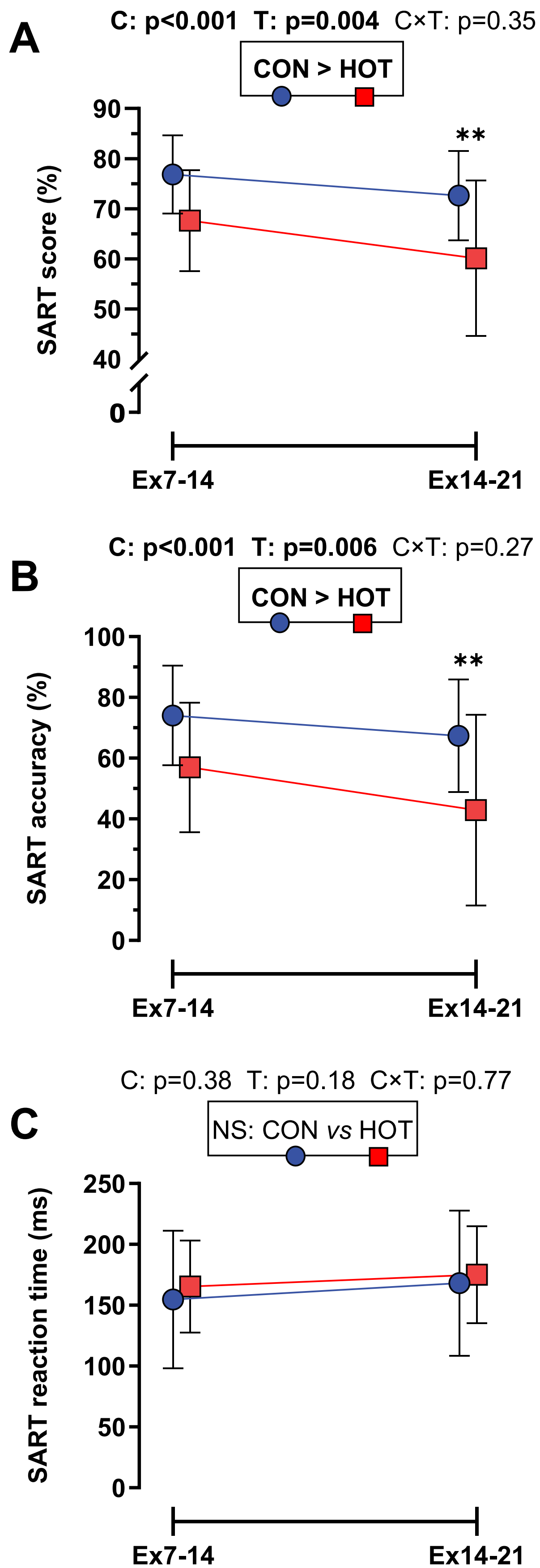

Figure 3. SART score (panel A), SART accuracy (panel B) and SART reaction time (panel C) during fixed-power cycling (Ex7-14, Ex14-21) in hot (HOT) or temperate (CON) environment for N = 16. Data are presented as mean ± standard deviation. Boxed text presents the *group* effect and p-values for main effects of *condition* (C), *time* (T) and *condition* × *time* (C × T) are displayed above each panel. Post-hoc significant differences for *time* effect are marked with the following symbols: **: P-value ≤ 0.006 vs. respective previous time-point.

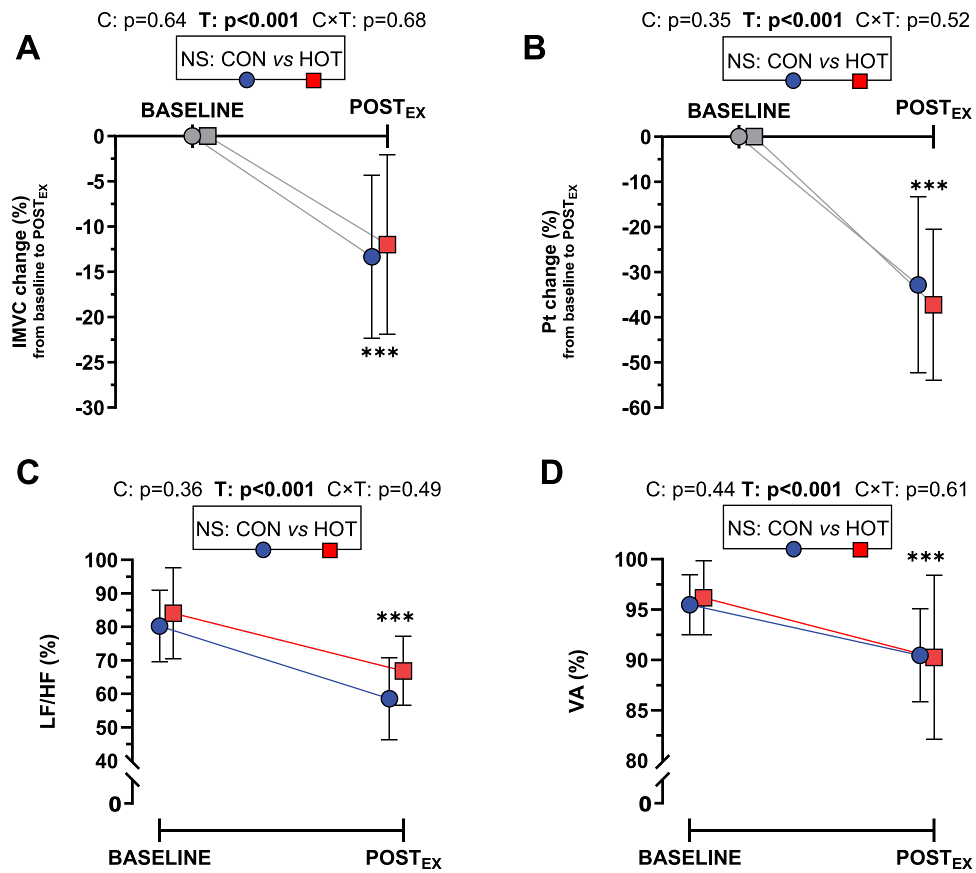

Figure 4. Change in isometric maximal voluntary contraction (IMVC, panel A), peak twitch (pt, panel B), low-frequency to high-frequency ratio (LF/HF, panel C) and voluntary activation (VA, panel D) from baseline to 1-min post-cycling ($POST_{EX}$) in hot (HOT) or temperate (CON) environment for N = 16. Data are presented as mean ± standard deviation. Boxed text presents the *group* effect and p-values for main effects of *condition* (C), *Time* (T) and *condition* × *Time* (C × T) are displayed above each panel. Post-hoc significant differences for *Time* effect are marked with the following symbols: ***: P-value <0.001 vs. baseline.

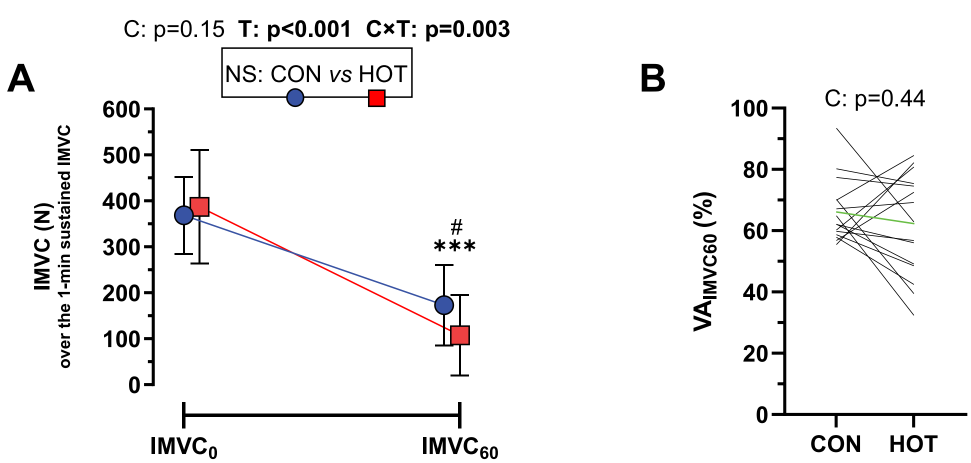

Figure 5. Change in 1-min sustained isometric maximal voluntary contraction (IMVC, panel A) from the start ($IMVC_0$) to the end ($IMVC_{60}$) and voluntary activation assessed at $IMVC_{60}$ (VA_{IMVC60}, panel B) in hot (HOT) or temperate (CON) environment for N = 16. VA is presented as individual values (black lines) with the averages (green line). IMVC is presented as mean ± standard deviation. Boxed text presents the *group* effect and p-values for main effects of *condition* (C), *Time* (T) and *condition* × *Time* (C × T) are displayed above each panel. Post-hoc significant differences for *Time* effect are marked with the following symbols: ***: P-value <0.001 vs. baseline. For *condition* × *Time* interaction are marked with the following symbols: #: P-value = 0.024 between conditions at $IMVC_{60}$.

$IMVC_{60}$ (−65 ± 38 N, P = 0.024). For VA_{IMVC60}, no *condition* effect was reported ($F_{(1, 15)}$ = 0.6, P = 0.44, FIGURE 5B).

Perceived cycling effort, mental effort and thermal discomfort

For cycling effort, a main effect of *condition* ($F_{(1, 15)}$ = 7.7, P = 0.014, η_p^2 =0.34), *time* ($F_{(2, 30)}$ = 23, P <0.001, η_p^2 =0.61) and *condition* × *time* interaction ($F_{(2, 30)}$ = 5.3, P = 0.011, η_p^2 =0.26) were reported (Figure 6A). Cycling effort increased between Ex7 and Ex14 (+5 ± 2 a.u., P = 0.005) and between Ex14 and Ex21 (+7 ± 4 a.u., P = 0.002), with higher values reported in HOT compared to CON (+5 ± 4 a.u., P = 0.014). For mental effort, a main effect of *time* ($F_{(2, 30)}$ = 42, P <0.001, η_p^2 =0.73) was reported (Figure 6B) with no *condition* effect (P = 0.14) or *condition* × *time* interaction (P = 0.099) reported. Mental effort increased between Ex7 and Ex14 (+20 ± 6 a.u., P <0.001) and between Ex14 and Ex21 (+10 ± 4 a.u., P <0.001). For thermal discomfort, a main effect of *condition* ($F_{(1, 15)}$ = 7.6, P = 0.015, η_p^2 =0.33), *time* ($F_{(2, 30)}$ = 58, P <0.001, η_p^2 =0.80) and *condition* × *time* interaction ($F_{(2, 30)}$ = 18, P <0.001, η_p^2 =0.54) were reported (Figure 6C). Thermal discomfort increased between Ex7 and Ex14 (+1.8 ± 0.3 cm, P <0.001) and between Ex14 and Ex21 (+0.9 ± 0.4 cm, P = 0.003), with higher values reported in HOT compared to CON (e.g., +1.8 ± 0.8 cm at Ex21, P = 0.004).

Discussion

The aim of this study was to investigate self-paced cycling based on perceived effort, CMDT performance, and neuromuscular fatigue, in hot and temperate environments in trained athletes. The main findings were that: (i) self-paced power was reduced by 11 ± 8% in the heat; (ii) attentional performance during cycling decreased by 15 ± 11% in the heat, and was accompanied by a steeper increase in HR and cycling effort, while T_{rec} and perceived mental effort remained similar; and (iii) a 36 ± 32% greater loss of force during sustained contraction after cycling in the heat, although peripheral and central fatigue components were similarly negatively affected across environments.

Heat affects self-paced exercise and cardiovascular drift

Self-paced exercise was used to evaluate how trained athletes spontaneously regulate workload under thermal stress. For a matched ‘strong’ cycling effort (i.e., 50 a.u. on the CR_{100}), participants blindly selected lower power in HOT vs. CON (−25 ± 10 W) yet showed a greater drift in HR and cycling effort once power could no longer be adjusted and workload was kept fixed (Ex7-Ex21). This aligns with previous work showing that fixed-intensity protocols often lead to increase physiological demand and premature exhaustion in hot environments, whereas self-paced models allow for recalibration of effort and prolonged activity (Schlader et al., 2011; Tatterson et al., 2000). In our study, T_{rec} was similar across conditions (~38.5 ± 0.4°C at Ex21), suggesting that the reduction in external workload lowered metabolic heat production and consequently decreased the rate of heat storage, thereby counterbalancing the additional thermal strain imposed by the external heat stress. Sweat losses were similar between conditions (~1.4 ±0.5 $L \cdot h^{-1}$), which may reflect a balance between higher metabolic heat production in temperate conditions and greater skin temperature driven sudomotor activity in the heat (Shibasaki, 2010), although skin temperature was not directly measured. This compensatory behaviour is reminiscent of hypoxia paradigms, where a reduced VO_2max lowers the sustainable workload for a given perceived effort, leading to comparable pacing adjustments despite different physiological constraints (Goepp et al., 2024; Mira et al., 2020). Thermal discomfort was markedly increased in the heat, likely reflecting the influence of cutaneous afferents, rather than core temperature *per se*, on perceptual regulation, even without direct measurement of skin temperature (Schlader et al., 2011). Overall, the self-paced methodology provides a relevant exercise prescription under heat stress, illustrating how athletes adjust workload to maintain internal strain within tolerable limits.

A novel design: Interaction between heat and cognitive-motor dual-task

Our findings extend previous literature by showing that CMDT performance was more impaired in HOT vs. CON (SART score: −10.8 ± 4.2%), despite similar T_{rec} at the end of exercise. These findings partially support our hypothesis and emphasise the innovative nature of our protocol, which more closely reflects real-world demands compared to traditional laboratory models (Schlader et al., 2022). While both SART accuracy and reaction time were measured, effects were mainly observed on the accuracy dimension, driving the decrease in overall SART score. This is consistent with previous findings using the same paradigm and reflects the task-dependent nature of the outcomes (Goepp et al., 2024). Additionally, previous research suggests that accuracy is a more sensitive indicator of high-intensity exercise stress than reaction time, particularly in trained individuals (Browne et al., 2017). In contrast, less fit

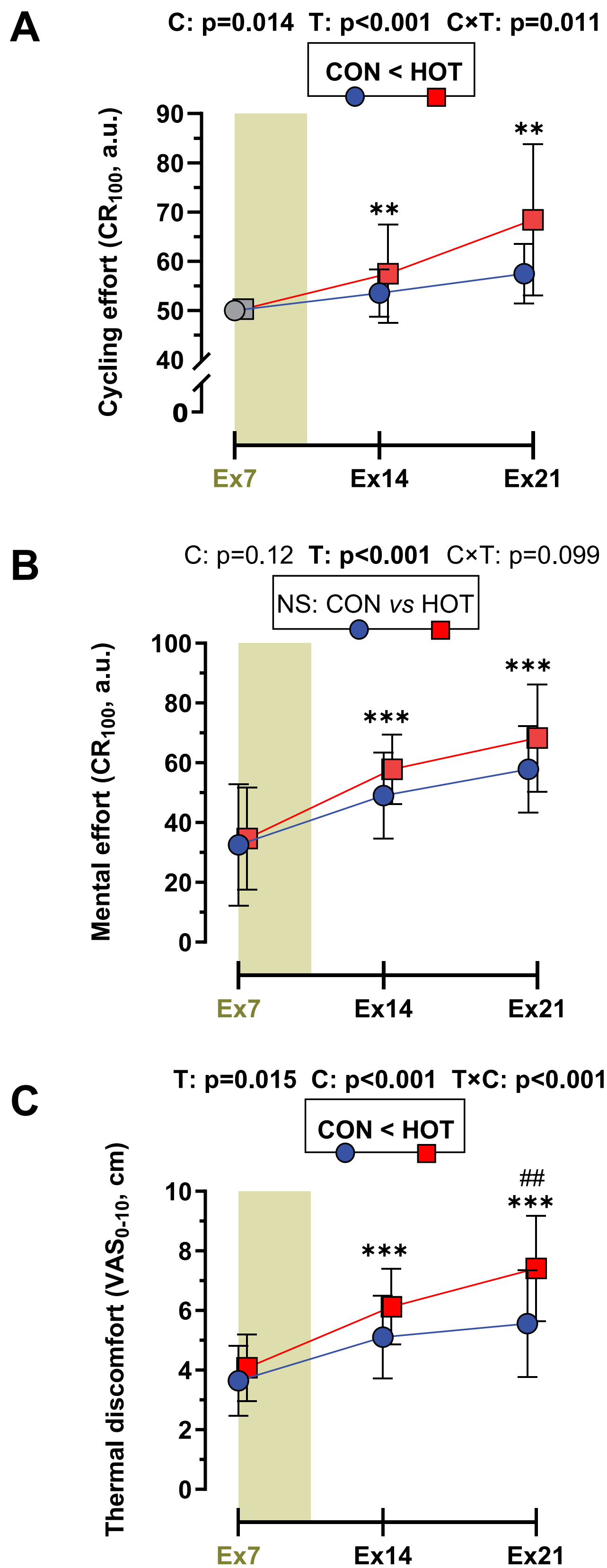

Figure 6. Perceived cycling effort (panel A), mental effort (panel B) and thermal discomfort (panel C) during self-paced cycling (brown area, Ex7) followed by fixed-power cycling with the SART task (Ex14, Ex21) in hot (HOT) or temperate (CON) environment for N = 16. Data are presented as mean ± standard deviation. Boxed text presents the *group* effect and p-values for main effects of *condition* (C), *Time* (T) and *condition* × *Time* (C × T) are displayed above each panel. Post-hoc significant differences for *Time* effect are marked with the following symbols: **(*): P-value ≤ 0.005 (<0.001) vs. respective previous time-point. For *condition* × *Time* interaction are marked with the following symbols: ##: P-value = 0.004.

populations often exhibit impairments in both metrics (Labelle et al., 2013). This dissociation in our findings may reflect a strategic preservation of processing speed at the expense of accuracy, or a specific vulnerability of the neural processes governing sustained attention under thermal strain (Dietrich & Audiffren, 2011).

Several mechanisms may explain this impairment, such as the increased perception of cycling effort. Indeed, prior work has shown that a greater drift in physical effort is associated with more pronounced cognitive impairment (Goepp et al., 2024). In line with the interoceptive hypothesis (McMorris, 2020), it is probable that the increased integration of peripheral signals, exacerbated by thermal strain, competed for limited central resources, thereby diminishing the performance of the concurrent cognitive task. Second, while hyperthermia is known to reduce cerebral blood flow and potentially compromise cortical recruitment for sustained attention (Qian et al., 2015), the degree of hyperthermia observed here was modest and comparable between conditions. However, previous studies suggest that a rapid rise in skin temperature, occurring even before significant hyperthermia, may be associated with cognitive impairment (Gaoua et al., 2012). It could be argued that higher skin temperature enhances local sensory discomfort (e.g., facial sweating), acting as a cognitive distractor. However, in our study, whole-body sweat rates were similar between conditions, suggesting that other mechanisms, likely related to the higher thermal discomfort specifically induced by the hot environment, were at play. Interestingly, perceived mental effort did not differ between conditions despite poorer cognitive performance in the heat. One plausible interpretation is that mental effort ratings may be less reliable when thermal and physical loads overlap, due to concurrent afferent inputs and altered perception, particularly in the context of a demanding CMDT (Wallman-Jones et al., 2021).

Finally, our observation that T_{rec} increased rapidly (+0.9 ± 0.2°C in less than 30 min) suggests that absolute hyperthermic thresholds (e.g., 38.5°C as 'optimal' for cognition) may be less informative than the individualised relative increase in core temperature from baseline, with cognitive performance likely affected at lower temperatures depending on task difficulty and exercise intensity. This observation may contest previous assertions that 38.5°C represents the critical threshold for cognitive decline (Schmit et al., 2017). This view is supported by recent findings showing that the speed and extent of thermal load, rather than a fixed temperature threshold, critically influence cognitive performance (Doohan et al., 2023). Overall, CMDT impairment in the heat appears to be driven more by perceptual influence than by the attainment of absolute core temperature thresholds; however, further research involving the monitoring of cerebral blood flow or skin temperature is warranted to further elucidate these mechanisms. Interestingly, neuromuscular indices were not exacerbated following the hot condition.

Knee-extensor force and neuromuscular fatigue: Central-peripheral mechanisms under heat

Neuromuscular responses were assessed through short IMVC, twitch interpolation, and a 1-min sustained IMVC. Short IMVC measured immediately post-exercise did not differ between HOT and CON, despite a noticeable time effect (−12.7 ± 9.5% from baseline. Similar patterns were observed for Pt, VA, and LF/HF ratio. This lack of condition effect on classical neuromuscular indices is likely due to the ~30-s delay between exercise cessation and evaluation, allowing partial recovery of central mechanisms, as previously reported (Gruet et al., 2013). These findings align with prior work in isolated self-paced or time-trial cycling, where comparable internal load or hyperthermia produced similar levels of central and peripheral fatigue despite environmental differences (Périard et al., 2011; Roussey et al., 2018). It is likely that the compensatory reduction in self-selected power output during the HOT trial offset the additional thermal strain, resulting in maximal neuromuscular fatigue levels (i.e., brief IMVC, VA, and Pt) similar to those observed in the CON trial. However, this pacing strategy did not prevent the impairment in sustained neuromuscular performance (i.e., 1-min sustained IMVC), suggesting that while maximal capacity was preserved through pacing, the ability to resist fatigue during a continuous effort remained specifically sensitive to heat stress. Notably, the present study extends these observations to a novel CMDT context, where high attentional demands may exacerbate declines in VA (Goepp et al., 2024, 2025). In the present study, lower power output for a given perceived intensity, combined with CMDT already taxing brain resources, may have masked any central differences between conditions. Additionally, all participants were well trained (Tier 2), conferring a high tolerance to heat stress independent of heat acclimation (McLellan, 2001). This may account for the small differences observed between conditions in both core temperature and neuromuscular fatigue.

However, to partially address methodological limitations (i.e., delays of evaluation in temperature environment), a 1-min sustained IMVC was performed, revealing a greater decline in HOT compared with CON (respectively at $IMVC_{60}$: −69.3 ± 11.9% vs. −59.3 ± 13.3%), whereas VA_{IMVC60} remained similar across environments. The greater force decline observed in HOT suggests that heat can exacerbate neuromuscular fatigue (Racinais & Oksa, 2010), but this effect was not clearly observed in the present study (i.e., no significant changes in peripheral or central indices), likely due to methodological choices. Overall, these results suggest that while CMDT under heat does not further impair VA *per se*, it amplifies global fatigue via integrated central and peripheral mechanisms, highlighting the complex interplay between cognitive load, environmental stress, and neuromuscular performance.

Limitations

Despite the innovative combination of CMDT in the heat, self-paced exercise, and neuromuscular fatigue assessments, several limitations should be acknowledged. First, the order of experimental conditions was not randomised due to logistical constraints (cf. *Experimental design* section), potentially introducing carry-over effects that could have influenced cycling pacing strategies, concurrent cognitive performance, or maximal sustained contractions. We believe that if anything, the implemented order effect is such that heat preceding cool trials would have reduced the magnitude of difference between conditions thus we believe the outcomes will be robust to future examination in a randomised order design. Additionally, neither convective airflow nor solar radiation, both recognised to influence heat stress (Périard et al., 2021), were simulated in the thermal chamber, which limits the ecological validity of these findings. Another important methodological limitation is the ~30-s delay between exercise cessation and the start of the neuromuscular assessment, combined with the transition to a temperate testing environment (cf. safety reasons). Together, these factors may have allowed partial recovery and reduced the detection of heat-induced neuromuscular alterations, particularly those involving central mechanisms of fatigue. Furthermore, due to the small female sample size, these findings should be selectively assessed in female participants to further elucidate the influence of biological sex on thermoregulation (Goncalves Costa et al., 2025). Last, dehydration was moderate in both conditions (−1.1 ± 0.3% change in BM), which may be a confounding variable influencing mechanistic understanding. Future studies should address these methodological limitations and incorporate additional physiological measurements (e.g., cerebral blood flow, skin temperature) to better understand the observed impairments in cognitive performance under heat stress, and whether heat alleviation strategies can ameliorate this deficit (Waldron et al., 2020).

Conclusion

This study provides empirical evidence that attentional performance during the CMDT was impaired in the heat, likely due to an exacerbated cardiovascular response. Self-paced power was reduced in the heat, resulting in comparable rectal temperatures at the end of the task. Although we were not able to identify differences in peripheral and central fatigue indicators across conditions, overall fatigue was greater in the heat. These findings provide valuable insight into CMDT under thermal stress, highlighting the need for targeted preparation in elite athletes or professional contexts exposed to such conditions. Future studies should explore strategies to mitigate the detrimental effects of heat on CMDT performance, such as heat acclimation or pacing interventions.

Author contributions

CRediT: **Thomas Goepp:** Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing; **Thomas Rupp:** Conceptualization, Methodology, Supervision, Writing – review & editing; **Oliver R. Gibson:** Conceptualization, Project administration, Writing – review & editing; **Mark Hayes:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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