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Evidence that heat acclimation training may alter sleep and incidental activity

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ABSTRACT

This randomized cross-over study tested the hypothesis that heat acclimation training would detrimentally affect sleep variables and alter incidental physical activity compared to a thermoneutral training control condition. Eight recreationally trained males ($\dot{V}O_{2peak}$ 49±4.9 mL·kg^{-1}·min^{-1}) completed two separate interventions separated by at least 31 days: 5 consecutive day training blocks of moderate-intensity cycling (60 min·day^{-1} at 50% peak power output) in a hot (34.9±0.7 °C and 53±4 % relative humidity) and a temperate (22.2±2.6 °C; 65±8 % relative humidity) environment. Wrist-mounted accelerometers were worn continuously for the length of the training blocks and recorded physical activity, sleep quality and quantity. Data were analysed in a Bayesian framework, with the results presented as the posterior probability that a coefficient was greater or less than zero. Compared to the temperate training environment, heat acclimation impaired sleep efficiency (Pr $\beta<0 = .979$) and wake on sleep onset (Pr $\beta>0 = .917$). Daily sedentary time was, on average, 35 min longer (Pr $\beta>0 = .973$) and light physical activity time 18 min shorter (Pr $\beta>0 = .960$) during the heat acclimation period. No differences were observed between conditions in sleep duration, subjective sleep quality, or moderate or vigorous physical activity. These findings may suggest that athletes and coaches need to be cognisant that heat acclimation training may alter sleep quality and increase sedentary behaviour.

Highlights

- Five consecutive days of heat training negatively affected some objective measures of sleep quality and incidental physical activity in recreationally trained athletes.
- Athletes and coaches need to be aware of the potential unintended consequences of using heat acclimation on sleep behaviours.

KEYWORDS
extreme environments; actigraphy; physical activity; training load; perceived exertion; stress

Introduction

Monitoring training load is especially pertinent during periods of deliberate intervention or intense scheduling to achieve program goals (Borresen & Lambert, 2009). Training in hot conditions is often used to accelerate cardiovascular, neuromuscular and perceptual adaptations that enhance subsequent exercise performance (Périard et al., 2015). However, the additional physiological strain induced from a hot environment amplifies the internal training load and exacerbates fatigue due to the higher relative intensity of any given mechanical load (Crowcroft et al., 2015). Exercise in the heat reportedly increases inflammation, alters hormonal activity, and activates the hypothalamic–pituitary–adrenal (HPA) axis (Rhind et al., 2004), resulting in a somatic stress reaction that disrupts sleep structure (Buguet et al., 1998). Accordingly, frequent athlete monitoring is crucial during heat acclimation training to avoid unplanned overreaching and impaired recovery. Such monitoring could potentially be achieved through a combination of recovery and off-training measurements, such as sleep and incidental activity data.

Sleep is a fundamental biological requirement to maintain adequate physiological and psychological

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function. The restorative and recuperative effects of sleep likely enhance exercise training adaptation (Fullagar et al., 2015). Conversely, there is evidence that sleep loss negatively affects an athlete's mood state (Scott et al., 2006) and can impair recovery (Banks & Dinges, 2007). Increased training loads, such as during a training camp or other intensified periods of cumulative exercise, are negatively associated with subjective sleep quality and may result in overreaching (Jürimäe et al., 2004). Environmental heat exposure, such as experienced during heat acclimation, may also compound the detrimental effect of intensified training on sleep indices, with previous research reporting decreases in subjective sleep quality and total sleep time (Skein et al., 2018), or conversely, increased awakenings after sleep onset and reduced sleep efficiency (Pitchford et al., 2017). However, the equivocal nature of these results may be related to the lack of standardised heat exposure (Pitchford et al., 2017) or a workload-matched training comparison (Skein et al., 2018). Regardless, the ability to quantify and measure the sleep patterns of athletes during heat acclimation training would provide valuable information on the response to training stress and may contribute to optimal athletic performance and recovery.

Accelerometer-based motion sensors are often used to track sleep duration and quality in athletes, thanks to their ease of wear and high agreement (~80–90%) with polysomnography (de Souza et al., 2003; Sargent et al., 2016). These sensors can also measure physical activity from accelerometer output, conveniently capturing unplanned incidental exercise during daily living as well as structured training sessions (Westerterp, 1999). Unlike sleep, monitoring incidental physical activity for training load in athletes has received less attention, despite initial suggestions that elite sportspeople may be surprisingly sedentary when not training (Weiler et al., 2015; Sperlich et al., 2017). Incidental physical activity has been hypothesised to potentially assist in recovery and support training adaptations, in a manner mechanistically similar to active recovery strategies (Izzicupo et al., 2019). Therefore, accelerometer-based physical activity assessments may inform behavioural and lifestyle modifications that complement physical performance goals. Moreover, when coupled with standard in-session training load measures (e.g. perceived training load, self-reported mood and fatigue, heart rate indices, and physical performance), sleep and incidental activity monitoring may offer a more holistic understanding of health and adaptative response to a training program (Düking et al., 2018).

To the best of our knowledge, accelerometer-based monitoring of training stress during heat acclimation training has not been rigorously investigated. While the effect of heat acclimation training on sleep indices has been previously described, the lack of a workload-matched control condition has prevented a comparison between different relative training loads and the possible effect on sleep variables. Therefore, this exploratory study aimed to investigate the effects of heat acclimation training on sleep and incidental activity measures in recreationally trained athletes. It was hypothesised that heat acclimation training would detrimentally affect sleep variables and alter incremental physical activity compared to a thermoneutral training control condition.

Materials and methods

Participants

A convenience sample of eight healthy males provided their written informed consent to participate in this study. Their mean (SD) characteristics were: age 26.5 (1.8) years; height 181 (9) cm; nude mass 82 (12) kg; peak oxygen consumption ($\dot{V}O_{2peak}$) 49.3 (4.9) $mL{\cdot}kg^{-1}{\cdot}min^{-1}$; peak power output 347 (56) W; and peak heart rate (HR) 187 (13) $beats{\cdot}min^{-1}$. Participants were undertaking 3.6 (1.3) training sessions per week; a total weekly training duration of 191 (63) min. Participants were classified as recreationally trained (performance level 2; $n = 7$) or trained (performance level 3; $n = 1$) (De Pauw et al., 2013). Written informed consent was provided by all participants. All experimental procedures adhered to the standards set by the latest revision of the Declaration of Helsinki, except for registration in a database, and were approved by the Human Research Ethics Committee of Queensland University of Technology (approval number: 1700000651).

Study design

This randomized, controlled cross-over study is an exploratory secondary analysis of a larger study, which examined the effect of short term heat acclimation training on cycling performance (Osborne et al., 2021). Participants completed five consecutive days of training in a temperature environment and in the heat. The sessions in the heat were completed in a specialised environmental climate chamber set to 34.9°C (0.7) and 53% (4) relative humidity and the thermoneutral training control condition was completed in a climate-controlled laboratory set to 22.2°C (2.6) and 65% (8) relative humidity. A training day consisted of 60 min of ergometer cycling at 50% peak power output. All training sessions were undertaken at the same time of day for each participant (±2 hours), and there was a minimum washout of 31 days between the two conditions (mean (SD) 56 (22) days).

Peak oxygen consumption and peak power output tests

To determine relative training intensity (50% peak power output), participants completed an incremental cycling test (Excalibur Sport; Lode, Groningen, Netherlands) before each training block. The commencing load was 75 W with 25 $W \cdot min^{-1}$ step increases until volitional fatigue. Expired gas was collected breath-by-breath using a calibrated analyser (TrueOne 2400; ParvoMedics, Salt Lake City, USA) and averaged over a 15-second epoch. Peak power output was calculated as described by De Pauw et al. (2013):

$$PO_1 + \frac{T_2(PO_2 - PO_1)}{T_1}$$

where PO_1 is the power output of the final completed stage, PO_2 is the power output of the final uncompleted stage, T_1 is the stage duration (60 seconds), and T_2 is the time elapsed in the final uncompleted stage.

Training sessions

At the start of each training session, participants' hydration status was assessed from a mid-stream urine sample for specific gravity (PAL-10S; Atago Co. Ltd, Tokyo, Japan) and colour (scale: 1–8, increments of 1) (Armstrong et al., 2010). Nude body mass was recorded (WB-110AZ; Tanita Corp., Tokyo, Japan) and participants inserted a rectal thermistor (449H; Henleys Medical, Hertfordshire, England) ~12 cm past the external anal sphincter for measurements of rectal temperature (T_{re}). The thermistor was connected to a wireless logger (T-Tec 7 3E-RF; Temperature Technology, Adelaide, Australia). Participants were also fitted with a heart rate (HR) monitor and chest strap to continuously monitor HR responses (Polar Team^2; Polar Electro Oy, Kempele, Finland).

Participants then cycled at 50% peak power output (Wattbike Pro; Wattbike Ltd, Nottingham, United Kingdom) for 60 min in the prescribed environmental condition. Physiological strain was quantified using a modified version of the physiological strain index (PSI) proposed by Moran et al. (1998), with mean PSI values for each training day calculated using the equation:

$$PSI = 5\frac{(T_{rei} - T_{re0})}{(40 - T_{re0})} + 5\frac{(HR_i\text{-}HR_0)}{(HR_{max}\text{-}HR_0)}$$

where "T_{rei}" and "HR_i" are mean T_{re} and mean HR values on training day i; "T_{re0}" and "HR_0" are resting measurements of T_{re} and HR, recorded after 10 min of supine rest, two days before commencing the respective training block; "HR_{max}" is each participant's peak HR values determined from the peak oxygen consumption test undertaken before each training block; and finally, "40" reflects the theoretical upper limit of T_{re}, of 40 °C. Mean HR and T_{re} during cycling were calculated for each participant on each training day.

Rating of perceived exertion (RPE) (Borg, 1998) was recorded every 10 min during the exercise task. Participants were asked to rate their overall perception of effort, on a 15-point scale ranging from 6 "no exertion at all" to 20 "maximal exertion". A psychological well-being review questionnaire (McLean et al., 2010) captured participants' subjective feelings on five items: sleep quality, fatigue, general muscle soreness, stress levels, and mood. Each item was rated on a 5-point scale (increments of 1), with "1" representing the worst possible well-being (i.e. always tired, insomnia, very sore, highly stressed, highly annoyed/irritable/down) and "5" the highest well-being score (i.e. very fresh, very restful, feeling great, very relaxed, very positive mood). Participants' sleep and wake times from the previous night were also recorded in sleep diaries.

Actigraphy

Participants' sleep and physical activity were continuously recorded via actigraphy throughout the five days of training. 48 h before each training block, participants received a wrist-mounted accelerometer device (GT9X; ActiGraph, Pensacola, FL, USA) and wore the accelerometer continuously until 48 h after the five day training period; a minimum of seven consecutive nights. Accelerometers were worn on the non-dominant wrist and participants were instructed to only remove the device during periods of aquatic activity, such as showering. All devices were initialised using ActiLife software (v.6.13.3; ActiGraph, Pensacola, FL, USA). The sampling frequency was set at 30 Hz.

Actigraphy data processing

Participants' self-reported in bed and wake up times were entered into ActiLife software to define the sleep window (v.6.13.3; ActiGraph, Pensacola, FL, USA) and the Cole-Kripke algorithm (Cole, Kripke, Gruen, Mullaney, & Gillin, 1992) was used to distinguish sleep from wakefulness. The following sleep variables were calculated: total sleep duration; sleep latency (duration between bedtime and sleep onset); sleep efficiency (total sleep time as a proportion of total time in bed); and wake after sleep onset (total time spent awake after the initial sleep onset and before final awakening). Actigraphy-based measurement of sleep variables has been previously validated against polysomnography in normal adult subjects (Marino et al., 2013; Quante et al., 2018) and reported to have a higher level of reliability (Plekhanova et al., 2020).

Euclidian norm minus one (ENMO) gravitational unit were derived by calculating the vector magnitude of the raw acceleration signal using the equation:

$$\text{Vector magnitude} = \sqrt{(x^2 + y^2 + z^2)}$$

followed by subtracting a fixed offset of 1 to account for the static component of gravity. Negative values were rounded up to zero (van Hees et al., 2013). Time spent in sedentary, light, moderate, and vigorous intensity exercise/physical activity was based on the Euclidian norm minus one thresholds developed by Hildebrand et al. (2014, 2017). Non-wear periods were identified by summing the time blocks in which the standard deviation of the acceleration signal vector magnitude was <13 mg for ≥30 consecutive min (Ahmadi et al., 2020). Monitoring days were excluded from the analysis if non-wear exceeded ≥480 min·day^{-1}.

Data analysis

All analyses were undertaken using R (R Core Team, 2021). Missing data in variables ranged from 2.5% to 12.5% (Supplement 1) and were assumed to be missing at random. Missing values were not imputed. All models were fit in a Bayesian framework, using Stan with the brms interface (Bürkner, 2017). The dataset and R code are available from https://github.com/SciBorgo/heat-actigraphy.

Mean HR, mean T_{re}, mean RPE, sleep duration, wake after sleep onset, sedentary time and light, moderate and vigorous activity time, nude mass, urine specific gravity and urine colour were modelled with linear regression. Light, moderate, and sedentary time were logged before analysis to meet the assumption of normally distributed errors. Mean PSI (0–10) and sleep efficiency (0–100) were modelled using beta regression. Beta regression is a flexible distribution that can accommodate skewed error terms and is often used to model values between 0 and 1 (Smithson & Verkuilen, 2006). Mean PSI and sleep efficiency were transformed to the 0,1 interval by dividing by the upper limit (i.e. 10 and 100, respectively) (Smithson & Verkuilen, 2006). Sleep efficiency values of 1 (i.e. 100%) were shifted off the boundary by subtracting 0.0001, which does not affect values when back-transformed to the original scale and rounded (Smithson & Verkuilen, 2006). Sleep latency was modelled using Poisson regression because it is a count variable. Finally, pre-cycling ratings of sleep quality, fatigue, general muscle soreness, stress levels, and mood were modelled using ordinal regression, under the proportional odds assumption. All models included training day, condition (levels: control, heat acclimation training) and the training day by condition interaction as fixed factors. Models also included a random intercept for each participant in the study.

Weakly informative prior distributions were used for the regression coefficients and variance parameters of these models. Markov chain Monte Carlo (MCMC) procedures were used to generate posterior estimates of expected values, using eight chains, each with 20,000 iterations, a 50% burn-in and thinned by a factor of 5. Posterior estimates of interest were: (i) the mean and 95% credible interval (CrI) of regression coefficients; (ii) the posterior probability that a regression coefficient was greater than zero (Pr β>0) or less than zero (Pr β<0), depending on the direction of the effect; (iii) the mean and 95% credible interval of each condition across the training days, unless otherwise stated; and where relevant (iv) the mean difference (MD) and 95% credible interval between conditions; and (v) the posterior probability that the MD was greater than zero (Pr MD>0) or less than zero (Pr MD<0). The convergence of MCMC to the posterior distribution was assessed using trace plots. Posterior predictive checks were performed to assess the suitability of all chosen models.

Results

Training load data

Mean HR during cycling (Figure 1) was higher when training in the heat (β = 13.2 beats·min^{-1}, 95% CrI = 7.3, 19.0; Pr β>0 = 1), and there was evidence that mean HR decreased across the training block, irrespective of training environment (β = –1.1 beats·min^{-1}, 95% CrI = –2.4, 0.2; Pr β<0 = .957). There was condition (β = 0.2 °C, 95% CrI = 0.04, 0.4; Pr β>0 = .991) and training day by condition (β = –0.06 °C, 95% CrI = –0.112, –0.001; Pr β>0 = .976) effects on mean T_{re} (Figure 1). Mean T_{re} was higher in the heat on training days one (MD = 0.17 °C, 95% CrI = 0.03, 0.31; Pr MD>0 = .992) and two (MD = 0.11 °C, 95% CrI = 0.02, 0.21; Pr MD>0 = .989). Similarly, there were condition (β_{logit} = 0.1, 95% CrI = 0.1, 0.2; Pr β>0 = .999) and training day by condition (β_{logit} = –0.7, 95% CrI = –1.4, –0.01; Pr β<0 = .976) effects on mean PSI (Figure 1). Mean PSI values were higher when training in the heat on days one (MD = 2.4, 95% CrI = 0.7, 4.2; Pr MD>0 = .997), two (MD = 1.9, 95% CrI = 0.8, 3.0;

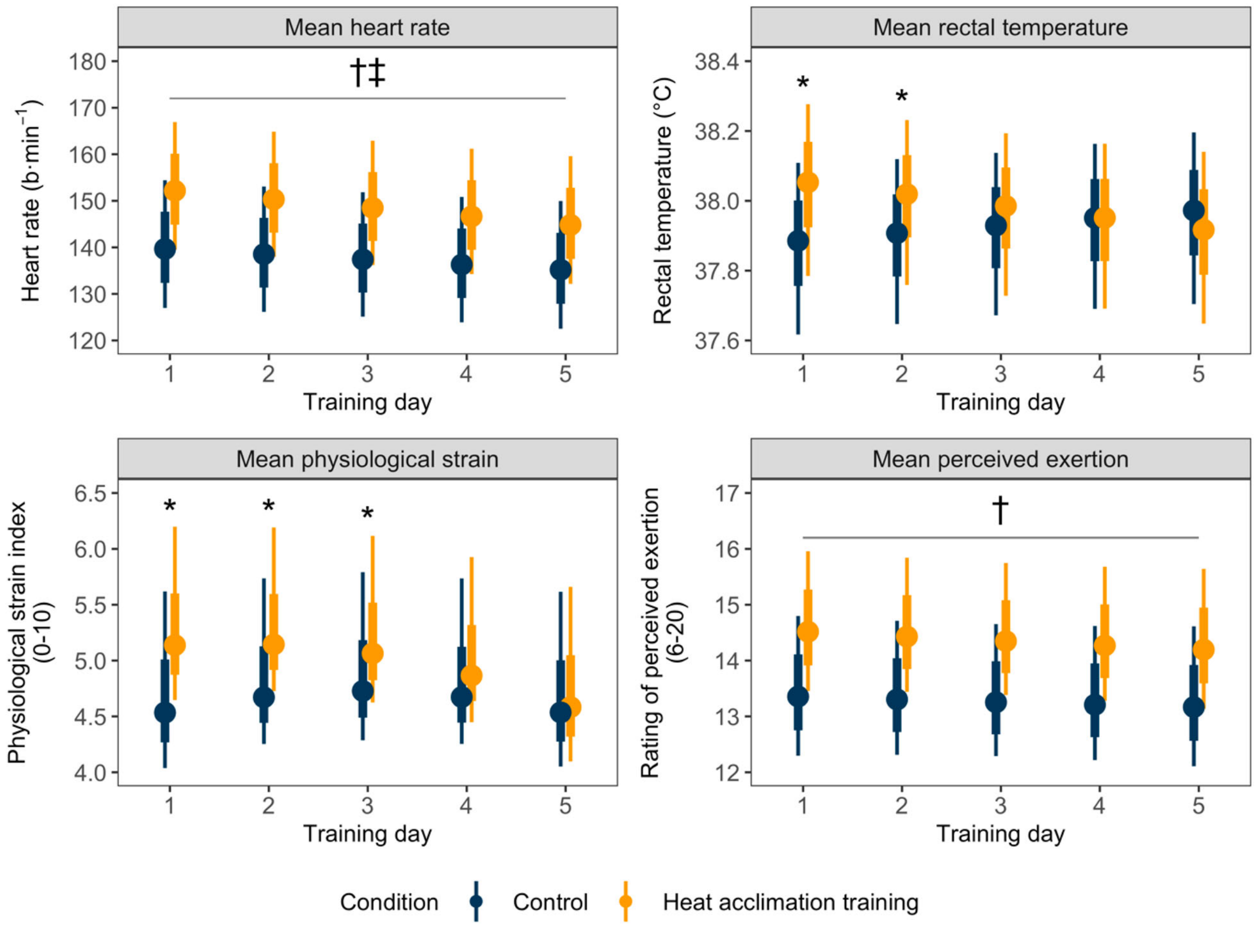

Figure 1. Mean training heart rate, rectal temperature, physiological strain, and rating of perceived exertion for the control and heat acclimation training conditions. Data are the posterior mean with 66% (thick inner line) and 95% (thin outer liner) credible intervals. On average, the mean heart rate was 13 beats·min^{-1} higher in the heat (indicated by †) and decreased across the training block, irrespective of condition (indicated by ‡). Mean rectal temperature was different between conditions on training days one and two (indicated by *). Mean physiological strain index values were different between conditions on training days one, two and three (indicated by *). The mean rating of perceived exertion was, on average, 1.2 units higher in the heat (indicated by †).

Pr MD>0 = 1) and three (MD = 1.3, 95% CrI = 0.1, 2.6; Pr MD>0 = .983). Mean RPE responses were higher when training in the heat (β = 1.2, 95% CrI = 0.3, 2.1; Pr β>0 = .995), by on average 1.2 units (Figure 1).

Sleep duration and quality

We removed 2/80 (2.5%) nights of sleep from the analysis because the accelerometer device was not worn (i.e. sleep duration was recorded as 0 min for the two nights). Sleep efficiency was lower in heat acclimation to a small extent (β_{logit} = −0.16%, 95% CrI = −0.32, −0.01; Pr β<0 = .979), by on average 2.1% (Figure 2). Sleep latency decreased across the training intervention (β = −3.4 min, 95% CrI = −6.6, −0.4; Pr β<0 = .987) but was not statistically different between conditions at any point. There was weak evidence that wake after sleep onset was longer with heat training (β = 7.6 min, 95% CrI = −3.3, 18.4; Pr β>0 = .917), by on average 7.6 min. We did not find any evidence that sleep duration (Figure 2) or perceived sleep quality (Table 1) were statistically different between conditions.

Incidental physical activity

Non-wear time was >0 min on 13/80 (16.3%) days of recordings. Of these 13 days, the median non-wear time was 45 min (interquartile range: 37–94; range: 31–374). There was evidence that when training in the heat, sedentary time was greater (β = 35.2 min, 95% CrI = −0.8, 70.8; Pr β>0 = .973) and light physical activity time lower (β = −0.10 min, 95% CrI = −0.20, 0.01; Pr β>0 = .960) compared to the thermoneutral training condition. Sedentary time was, on average, 35 min higher and light activity time was, on average, 18 min lower when training in the heat (Figure 3). Moderate and

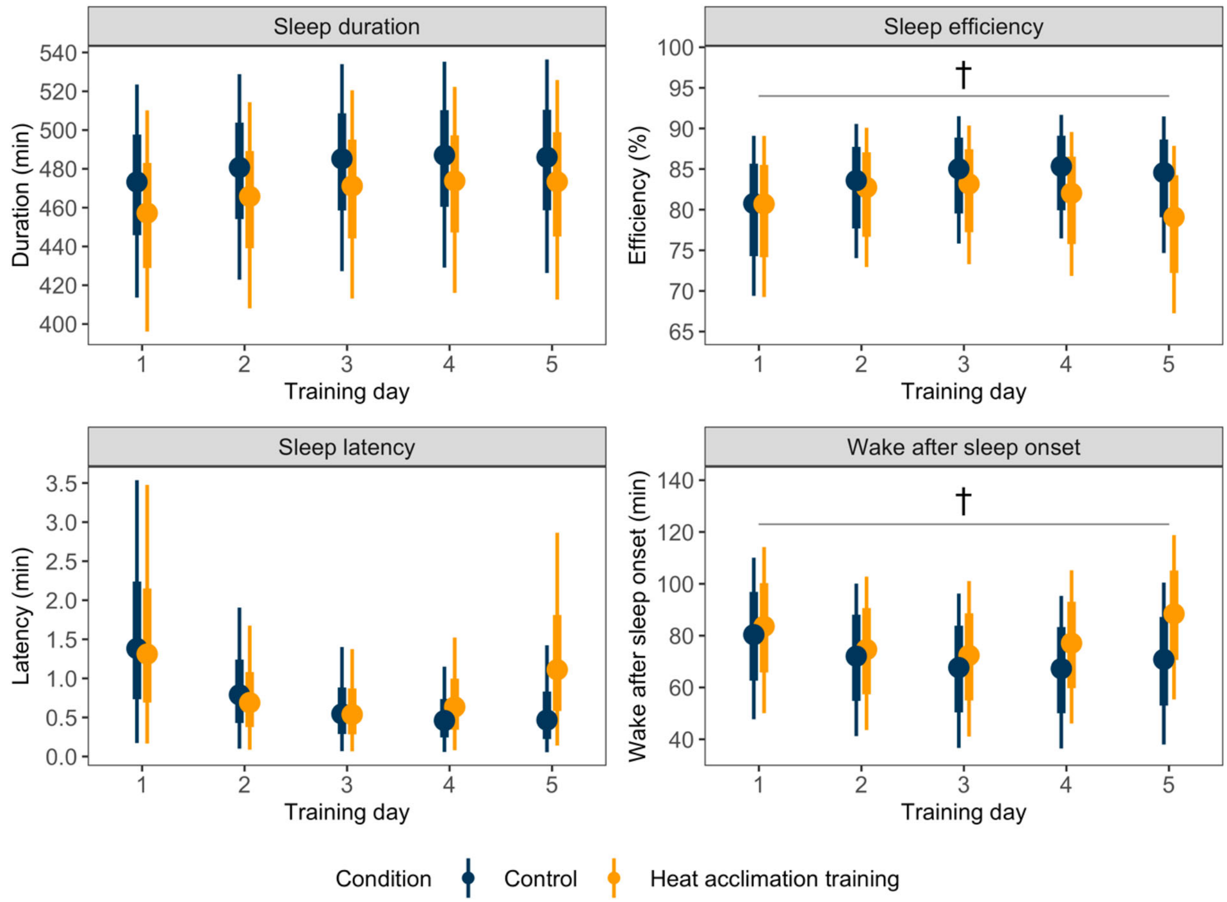

Figure 2. Sleep duration, efficiency, latency, and wake after sleep onset for the control and heat acclimation training conditions. Data are the posterior mean with 66% (thick inner line) and 95% (thin outer liner) credible intervals. Sleep efficiency was lower when training in the heat (indicated by †), by on average 2.1%. There was weak evidence that wake after sleep onset was longer during the heat training intervention (indicated by †), by on average 7.6 min.

vigorous physical activity times were not statistically different between conditions at any point (Figure 3).

Pre-cycling variables

Urine specific gravity increased across the training intervention ($\beta = 0.024$, 95% CrI = 0.001, 0.047; Pr $\beta > 0 = .979$), but was not statistically different between conditions at any point (Table 1). There was no evidence of *training day*, *condition*, or *training day* by *condition* effects on nude mass or urine colour (Table 1). No evidence of any main or interaction effects were noted for pre-exercise self-reported ratings of fatigue, mood, soreness, or stress (Supplement 2).

Discussion

This exploratory study tested the hypothesis that increased training stress, resulting from heat acclimation, would alter sleep and incidental physical activity

Table 1. Daily pre-cycling training variables.

Variable	Condition	Day 1	Day 2	Day 3	Day 4	Day 5
Nude body mass (kg)	Control	80.9 [57.3, 99.5]	81.0 [57.5, 99.5]	81.0 [57.5, 99.5]	80.9 [57.4, 99.4]	80.7 [57.1, 99.3]
	HA	80.5 [56.9, 99.1]	80.4 [56.9, 98.9]	80.4 [56.8, 98.9]	80.4 [56.9, 98.9]	80.6 [57.0, 99.2]
Urine specific gravity	Control	1.014 [1.006, 1.022]	1.017 [1.010, 1.024]	1.020 [1.012, 1.027]	1.021 [1.014, 1.028]	1.022 [1.013, 1.030]
	HA	1.018 [1.009, 1.026]	1.018 [1.011, 1.025]	1.018 [1.011, 1.025]	1.018 [1.010, 1.025]	1.017 [1.008, 1.025]
Urine colour (1–8)	Control	3 [2, 5]	4 [3, 5]	5 [3, 5]	5 [3, 5]	4 [3, 5]
	HA	4 [2, 5]	4 [2, 5]	4 [2, 5]	4 [2, 5]	4 [2, 5]
Subjective sleep quality (1–5)	Control	3 (2–3)	3 (2–3)	3 (1–3)	3 (2–4)	3 (3–3)
	HA	3 (3–3)	3 (2–3)	3 (3–3)	2 (1–3)	3 (3–3)

Note. HA = Heat acclimation training. Data presented as mean [range], except for subjective sleep quality, where values are median (interquartile range). *N* = 8 participants.

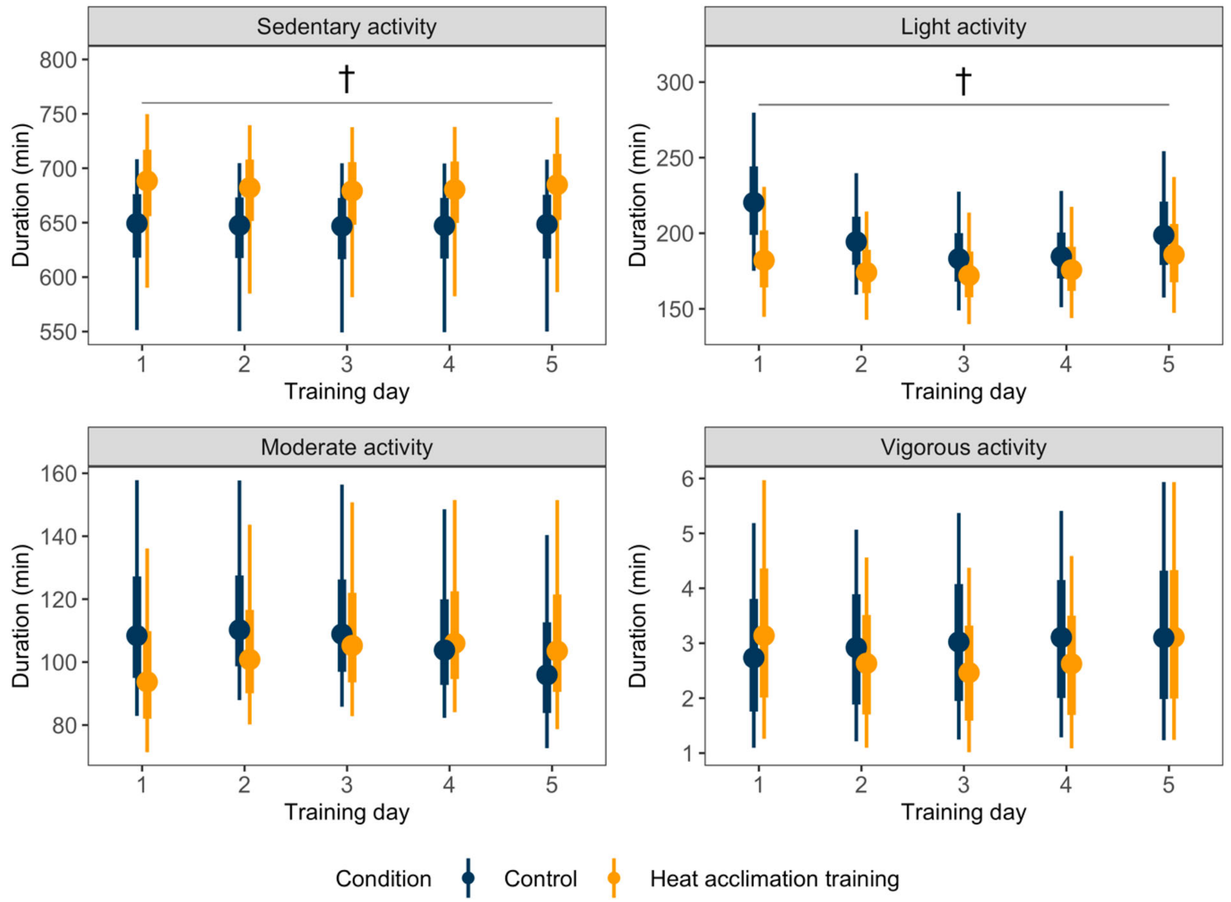

Figure 3. Sedentary time and light, moderate and vigorous physical activity time for the control and heat acclimation training conditions. Sedentary time was greater when training in the heat (indicated by †), by on average 35 min. Light physical activity time was lower when training in the heat (indicated by †), by on average 18 min less.

parameters compared to a thermoneutral training intervention. The novel findings of this research are, across five days of training in the heat compared to a thermoneutral environment, wrist-worn accelerometers: (i) indicated a small reduction in sleep quality (i.e. decreased efficiency and increased wake after sleep onset), (ii) reduced incidental physical activity (i.e. increased sedentary time and decreased light physical activity time) and (iii) no effects on sleep duration, sleep latency or subjective sleep quality, or time spent in moderate- or vigorous-intensity physical activity. Elevated training stress was observed in the hot environment compared to the control condition, as evidenced by higher HR, T_{re}, and PSI measures.

Heat acclimation training resulted in poorer sleep efficiency and an increased wake after sleep onset duration. As these two variables can be considered indicators of sleep quality (Pitchford et al., 2017; Roberts et al., 2019), this finding suggests that additional training stress from a hot environment appears to impair sleep quality. Similar outcomes have been previously reported, with consecutive training sessions in the heat reducing sleep quality, both objectively (Pitchford et al., 2017) and subjectively (Skein et al., 2018). However, study design differences make it challenging to compare these findings with the current study directly. For example, Pitchford et al. (2017) implemented field-based training in a moderately warm environment (29°C) without a specific focus on heat-acclimation training, limiting the relevance of the results to the present study. Interestingly, Skein et al. (2018) reported no significant effect of 5 days of heat acclimation training (32°C) on actigraphy-based measures of sleep quality; although self-reported sleep quality was noted as being of affected quality. This finding contrasts observations in the present study, where increased physiological and perceptual stress from heat-based training was not reflected in self-reported sleep quality. The contrasting results may be explained by the previously reported poor agreement between subjective sleep questionnaires and objective measures of sleep quality, documented in recreational (Kölling et al., 2016) and elite (Dunican et al., 2017) athletes. Further, Skein et al. (2018) did not include a thermoneutral training control group, meaning they could not isolate the effect of heat on sleep variables from training alone. The cross-over design used in the current study strengthens our findings that the additional stress induced by training in the heat disrupts sleep quality, particularly sleep efficiency. However, it is important to note that that the observed changes in these sleep variables were relatively small, and caution should be used when considering the practical significance of these differences on athletic sleep quality.

The increased training stress due to HA altered the off-training physical activity profiles, reducing light physical activity time and increasing sedentary time compared to temperate training. Although research describing the off-training physical activity in athletes is limited (Izzicupo et al., 2019), several previous studies have indicated that elite athletes may have higher levels of sedentary behaviour than the general public (Weiler et al., 2015; Sperlich et al., 2017), despite exceeding the recommended moderate- and/or vigorous-intensity physical activity guidelines. The causative factor(s) for elevated sedentariness in athletes is currently unknown. However, it has been speculated that training-induced fatigue may attenuate off-training physical activity behaviours (Franssen et al., 2021). The present findings support this hypothesis, with altered activity profiles, including increased sedentary time, indicating that participants may have modified their off-training behaviours to recuperate and recover from the elevated internal training load (Izzicupo et al., 2019). This study suggests that physical activity behaviours may offer insight into the relative training stressor response (Sperlich & Holmberg, 2017; Düking et al., 2018), with possible implications for understanding athlete readiness to train, perform, and recover in addition to their long-term health. However, the exploratory nature of our study should be noted, and further investigation in a larger sample is needed to confirm these findings.

Participants experienced increased stress from heat acclimation training, as evidenced by higher mean HR, PSI and RPE ratings across the five days of training compared to the control condition (Figure 1). While this heat-mediated increase in internal response to training (Crowcroft et al., 2015) may alter sleep and physical activity profiles, it is noteworthy that the increased training response was largely driven by cardiovascular rather than thermoregulatory strain, with only mild increases in T_{re} observed on heat training days one (0.17°C; Figure 1) and two (0.11°C). By undertaking the five days of cycle training, irrespective of the environment, participants experienced a marked increase in total training duration and intensity compared to their typical weekly training load. The entire five-day training duration was +57% longer than the participants' weekly training average (191 min) and was likely performed at a higher relative intensity for both HA (mean training HR = 81 (8)% HR_{peak}) and CON (mean training HR = 74 (5)% HR_{peak}). As cardiovascular strain was the primary driver of the increased stress, it remains to be seen if sleep quality and incidental physical activity profiles would be affected similarly when training under additional thermal stress. Investigation of the effects of heat acclimation on parameters of sleep and incidental physical activity profiles using an isothermic heat acclimation protocol is warranted (Périard et al., 2015). For context, the average time spent above 38.5°C in each training session was only marginally higher in the heat (16.7 min) compared to the control condition (13.7 min). Similarly, using more highly trained participants (e.g. performance level 3 and above (De Pauw et al., 2013) accustomed to high weekly training durations would provide greater insight into the effects of heat acclimation training on sleep and incidental physical activity.

Several considerations must also be acknowledged for this study. A primary limitation of the study is the small sample size, which was reflected in the uncertainty of some results. For example, while sleep duration was not statistically different between the conditions, there was also little indication that it was statistically equivalent ($\beta = -14.1$ min, 95% CrI = −42.2, 14.0; Pr $\beta<0 = .841$, Pr $\beta>0 = .159$). The results are likely specific to the group for which data was available and are by no means generalizable, and may not extrapolate to other groups, such as females and older athletes. However, the data does provide a direction for future research. It should be noted that the lack of baseline measurements for sleep and physical activity excluded the possibility of evaluating the effect of intensified training on these variables. As such, the study outcomes are limited to only a direct comparison between training block conditions and cannot assess the effect that intensified training alone may have on sleep and physical activity. The recreational training status of participants may have also influenced the results, as the intensified training block was considerably higher than their average weekly training volume.

Conclusion

This exploratory randomised cross-over study indicates that heat acclimation training may reduce some objective measures of sleep quality and alter incidental physical activity profiles, including an increased sedentary time, in recreational athletes. While participants experienced increased physiological stress when undertaking five days of cycle training in the heat, compared to a thermoneutral environment, this was due primarily to heightened cardiovascular strain, with only mild increases in thermoregulatory strain observed in the heat. Future studies are needed to confirm the generalisability of these results and should consider replication of the study using an isothermal acclimation protocol, and in more highly trained athletes who are accustomed to weekly training durations that match, or exceed, the heat acclimation training duration.

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