Journal of Sports Sciences

ISSN: 0264-0414 (Print) 1466-447X (Online) Journal homepage: http://www.tandfonline.com/loi/rjsp20

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To cite this article: Rebecca Relf, Ashley Willmott, Jessica Mee, Oliver Gibson, Arron Saunders, Mark Hayes & Neil Maxwell (2017): Females exposed to 24 h of sleep deprivation do not experience greater physiological strain, but do perceive heat illness symptoms more severely, during exercise-heat stress, Journal of Sports Sciences, DOI: 10.1080/02640414.2017.1306652

To link to this article: http://dx.doi.org/10.1080/02640414.2017.1306652

Published online: 24 Mar 2017.

JOURNAL OF SPORTS SCIENCES, 2017
http://dx.doi.org/10.1080/02640414.2017.1306652

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Females exposed to 24 h of sleep deprivation do not experience greater physiological strain, but do perceive heat illness symptoms more severely, during exercise-heat stress

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ABSTRACT

There is limited and inconclusive evidence surrounding the physiological and perceptual responses to heat stress while sleep deprived, especially for females. This study aimed to quantify the effect of 24 h sleep deprivation on physiological strain and perceptual markers of heat-related illness in females. Nine females completed two 30-min heat stress tests (HST) separated by 48 h in 39°C, 41% relative humidity at a metabolic heat production of 10 W · kg^{-1}. The non-sleep deprived HST was followed by the sleep deprivation (SDHST) trial for all participants during the follicular phase of the menstrual cycle. Physiological and perceptual measures were recorded at 5 min intervals during the HSTs. On the cessation of the HSTs, heat illness symptom index (HISI) was completed. HISI scores increased after sleep deprivation by 28 ± 16 versus 20 ± 16 (P = 0.01). Peak (39.40 ± 0.35°C vs. 39.35 ± 0.33°C) and change in rectal temperature (1.91 ± 0.21 vs. 1.93 ± 0.34°C), and whole body sweat rate (1.08 ± 0.31 vs. 1.15 ± 0.36 L · h^{-1}) did not differ (P > 0.05) between tests. No difference was observed in peak, nor rise in: heart rate, mean skin temperature, perceived exertion or thermal sensation during the HSTs. Twenty-four hours sleep deprivation increased perceptual symptoms associated with heat-related illness; however, no thermoregulatory alterations were observed.

ARTICLE HISTORY
Accepted 7 March 2017

KEYWORDS
Metabolic heat production; thermoregulation; sleep loss; heat injury; females

Introduction

Physically stressful occupational and athletic activities performed in hot conditions increase physiological strain and impair endurance performance (Galloway & Maughan, 1997). Uncompensable heat stress may increase the risk of developing a heat-related illness (HRI), through increased core temperature, cardiovascular strain and a substantial loss of fluids and electrolytes (Coris, Ramirez, & Van Durme, 2004). HRIs are categorised by severity and occur along a continuum, where relatively minor symptoms (e.g., heat rash or cramps) can rapidly progress into serious and life-threatening events (e.g., cognitive dysfunction, loss of consciousness) (Heled, Rav-Acha, Shani, Epstein, & Moran, 2004). HRI onset can be caused and exacerbated by a combination of risk factors including anthropometric characteristics, age, sex, acclimation state and sleep deprivation, with random or sporadic onsets (Moran, Heled, Still, Laor, & Shapiro, 2004).

Sleep deprivation has been reported to contribute to exertional heat illnesses in a multitude of occupational literature (McDermott et al., 2007). Furthermore, 83% of HRI cases were related to a prior episode of sleep deprivation (3–4 h per night) (Rav-Acha, Hadad, Epstein, Heled, & Moran, 2004). Contributing factors to HRIs while sleep deprived include the larger (+0.7°C) exercising core temperature (T_{re}) (Sawka, Gonzalez, & Pandolf, 1984), impaired sudomotor function (reduced ability to dissipate heat through evaporation) (Fujita, Lee, Ismail, & Tochihara, 2003; Sawka et al., 1984) and increments in ratings of perceived exertion (RPE) and thermal sensation (TS) (Muginshtein-Simkovitch et al., 2015). While sleep is a naturally recurring state, characterised by circadian periodicity (García-García, Juárez-Aguilar, Santiago-García, & Cardinali, 2014), sleep loss (<6.5 h recommended per night) and/or deprivation (e.g., partial or full) disrupts the circadian rhythm and is highly prevalent among healthy adults and adolescents (Fullagar et al., 2015). Moreover, sleep deprivation is associated with health risks (e.g., increase diurnal blood pressure and cortisol levels) and cognitive impairments (e.g., decision-making, memory) (Short & Banks, 2014). Acute 24 h sleep deprivation observed during operational duties such as nursing, mining, aviation and trucking negatively influences cognitive function, which may influence, and potentially cause, several catastrophic incidents and accidents (Horne & Reyner, 1995).

Aside from occupations, the multitude of athletes regularly travelling to environmentally challenging conditions (i.e., heat stress), across many time zones to train and compete, are exposed to short-term or chronic sleep loss/deprivation on a regular basis (Oliver, Costa, Laing, Bilzon, & Walsh, 2009). Whilst experiencing symptoms of HRI may not indicate a medically reportable case, it does suggest an increased susceptibility due to an increased physiological strain and emphasis that the body is unable to meet the demands of

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thermoregulation (Heled et al., 2004). In an attempt to assess and quantify milder forms of HRI, a heat illness symptom index (HISI) was developed (Coris, Walz, Duncanson, Ramirez, & Roetzheim, 2006). This was formed from an in-depth literature review analysing the most common symptoms associated with HRI, to which 13 were chosen (see Figure 2). The HISI was developed to allow a better understanding of the potential pathophysiologic and symptomatic progression of HRI, presenting good reliability and validity in American football players' training (Coris et al., 2006). However, correlation with core temperature was advised for further validation in relation to HRI.

A paucity of evidence exists surrounding the physiological and perceptual responses while sleep deprived, especially for females when acknowledging the differences in thermoregulatory function between sexes (Fujita et al., 2003; Oliver et al., 2009). Moreover, controlling for metabolic heat production ($\dot{H}_{prod}$) during sleep deprivation exercise protocols reduces the systematic differences in T_{re} despite differences in body mass and aerobic capacity (Cramer & Jay, 2014). Therefore, the aim of this study was to quantify the effect of acute sleep deprivation (24 h) on perceptual markers related to HRI and physiological strain in females when menstrual cycle is controlled for. It was hypothesised that sleep deprivation would increase the perception of symptoms of HRI, determined by an increased HISI score. Second, sleep deprivation would significantly increase the rate of T_{re} rise during exercise.

Method

Participant characteristics and requirements

Nine recreationally active females (mean ± standard deviation (SD); aged: 22 ± 3 years, stature: 1.66 ± 0.10 m, body mass: 63.8 ± 10.6 kg, body surface area (BSA):1.7 ± 0.2 m^2, peak oxygen uptake ($\dot{V}O_2$peak) in 40.1 ± 0.4°C, 42 ± 1% relative humidity: 44.1 ± 3.4 mL · kg^{-1}.min^{-1}) volunteered and provided prior written informed consent. Participants had regular sleeping patterns confirmed by sleep diaries (average of >6.5 h per night) and had not been exposed to heat stress in the month prior to testing, nor had previously incurred a HRI. The study was approved by the University of Brighton's ethics committee and conformed to the revised Declaration of Helsinki (World Medical Association, 2013). Participants abstained from caffeine (Muginshtein-Simkovitch et al., 2015), strenuous exercise and alcohol in the 24 h prior to testing. Moreover, no food was consumed within the 2 h prior to each trial and participants were instructed to consume 3–5 mL · kg^{-1} of water during this period (Sawka et al., 2007). All testing occurred in the morning (08:00–10:00) to control for circadian rhythm. Self-reported menstrual cycle questionnaires were completed in order to schedule testing, which occurred in the early follicular stage of their menstrual cycle (Day 0–7), as higher resting T_{re} (0.3–0.6°C) and a delayed onset of sweating and cutaneous vasodilation have been reported to occur in the luteal phase (Pivarnik, Marichal, Spillman, & Morrow, 1992). Participants taking oral contraceptive pills undertook testing during the no pill, placebo phase; these timings were selected to control for hormonal fluctuations in line with previous literature (Stachenfeld & Taylor, 2014).

Experimental design

Participants undertook a repeated measures design, requiring three visits to the laboratory: a lactate threshold and $\dot{V}O_2$peak test, a heat stress test (HST) and finally a sleep deprived HST (SDHST), all separated by 48 h. Due to the time restriction of completing tests during the follicular phase of the menstrual cycle, the sleep deprivation test was completed last as the recovery period is still unclear within the literature (Belenky et al., 2003). These logistical constraints necessitated the order of trials and non-randomised approach.

Preliminary testing

Lactate threshold and $\dot{V}O_2$peak

The pre-programmed lactate threshold protocol was standardised for all participants, beginning at 5 km · h^{-1} on a motorised treadmill (Woodway, Germany) within a purpose-built environmental chamber (TISS, UK) set to 39.9 ± 0.8°C and 41 ± 3% RH. Participants performed five submaximal (Jay, Bain, Deren, Sacheli, & Cramer, 2011), 3 min incremental stages of 0.8 km · h^{-1} (Spurway & Jones, 1997) at 1% gradient (Jones & Doust, 1996). Expired air was collected using open-circuit spirometry for 45 s in the last minute of each stage to estimate metabolic heat production for prescription of workload for the subsequent HSTs. Each Douglas bag was analysed using a gas analyser (Servomex International Ltd., UK) to give oxygen (O_2) and carbon dioxide (CO_2) percentages. The temperatures and volumes of the gases were acquired using a dry gas flow meter (Harvard Apparatus Ltd., UK) and a fixed flow pump model Dymax 30 (Charles Austin Pumps Ltd., UK). A two-point calibration was undertaken using a mixture of gases and predetermined O_2 and CO_2 percentages (15 and 5%, respectively) (BOC, UK) prior to every trial. T_{re}, heart rate (HR), TS (Toner, Drolet, & Pandolf, 1986) and RPE (Borg, 1982) were recorded at the end of each 3-min stage. Following a 15-min rest, participants began running at 8.0 km · h^{-1}, with 1 min stages and increments of 1.0 km · h^{-1} (James, Richardson, Watt, & Maxwell, 2014) until volitional exhaustion. Expired air was collected in a Douglas bag for 45 s during each stage, and HR and T_{re} were recorded at the end of each stage. Due to the physiological strain, $\dot{V}O_2$peak was obtained; it was not maximal as not all criteria were met (e.g., plateau in $\dot{V}O_2$) (Spurway & Jones, 1997).

Metabolic heat production ($\dot{H}_{prod}$)

In conformity with the recommendations from Jay et al. (2011) and Cramer and Jay (2014), $\dot{H}_{prod}$ was prescribed from metabolic energy expenditure and velocity during the running submaximal lactate threshold. Metabolic energy expenditure (Nishi, 1981) was calculated from each stage for oxygen consumption ($\dot{V}O_2$) and the respiratory exchange ratio (RER) (Jay et al., 2011), using the following equation:

$$M = \mathrm{VO}_2 \frac{\left(\frac{\mathrm{RER}-0.7}{0.3} e_c\right) + \left(\frac{1-\mathrm{RER}}{0.3} e_f\right)}{60} \times 1000\,\mathrm{Watts}$$

where e_c is the caloric equivalent per litre of O_2 for the oxidation of carbohydrates (21.13 kJ), and e_f is the caloric equivalent per litre of oxygen for the oxidation of fat (19.62 kJ). $\dot{H}_{prod}$ was determined as the difference between metabolic energy expenditure (M) and external mechanical power output (W), divided by body mass (BM) to obtain relative $\dot{H}_{prod}$ ($W \cdot kg^{-1}$): $\dot{H}_{prod} = (M–W)/BM$.

Main experimental tests

The HST consisted of 30 min running at a $\dot{H}_{prod}$ of 10 $W \cdot kg^{-1}$ (pre-determined by pilot work) at 1% gradient (Jones & Doust, 1996) on a motorised treadmill. The treadmill velocity did not differ between HSTs for each participant (8–10 $km \cdot h^{-1}$, 77 ± 5% $\dot{V}O_2peak$). The test occurred within hot conditions 39.8 ± 0.7°C and 41 ± 2% RH, which were controlled using automated computer feedback (WatFlow control system, TISS, UK).

Pre-trial preparation

On arrival to the laboratories, participants provided a fresh mid-flow urine sample. Euhydration was confirmed by the following criteria (Sawka et al., 2007): urine osmolality (Uosm) ≤700 $mOsm \cdot kg^{-1}$ H_2O (Advanced Micro Osmometer 3300, Vitech Scientific Ltd., UK) and specific gravity (Usg) ≤1.020 (URC-Ne handheld refractometer, ATAGO CO Ltd., Japan). Following this, nude body mass (NBM) was recorded to the nearest gram (GFK 150, Adam Equipment Inc., USA). Differences between pre- and post-exercise NBM determined non-urine fluid loss (whole body sweat rate, $L \cdot h^{-1}$). After a 15-min rest period, in a controlled laboratory (21.9 ± 1.7°C, 50 ± 10% RH), baseline measures were recorded.

Experimental measurements

Rectal probes (Henley, UK) were self-inserted 10 cm past the anal sphincter provided continuous T_{re} measurement throughout tests. Participants were familiarised to the HISI (0–130), TS (0 unbearably cold to +8 unbearably hot) and RPE (6 = very, very light to 20 = exhaustion) scales, and then affixed a HR monitor to the chest (Polar FT1, Polar Electro, Finland). Skin temperature (T_{skin}) was recorded using skin thermistors (Eltek Ltd, Cambridge, UK) attached to four sites: the midpoint of the right pectoralis major (T_{chest}), midpoint of the right triceps brachii lateral head (T_{arm}), right rectus femoris ($T_{upper\ leg}$) and right gastrocnemius lateral head ($T_{lower\ leg}$), and connected to a temperature logger (Squirrel 1000 series, Eltek Ltd., UK). This device has been found to have a typical error of measurement (TEM) of 0.18°C (James et al., 2014). T_{skin} was calculated using the following equation by Ramanathan (1964): Mean $T_{skin} = (0.3 \times [T_{chest} + T_{arm}]) + (0.2 \times [T_{upper\ leg} + T_{lower\ leg}])$. Both physiological and perceptual measurements were taken at 5 min intervals throughout the 30 min running HST. Expired air was collected at three time points during the run (minutes 4–5, 14–15 and 24–25) to assess the accuracy of the $\dot{H}_{prod}$ prescription. The HISI scale (Coris et al., 2006) is a 10-point index of 13 symptoms including that of thirst, dizziness, so on, which are rated on a scale of 0 (no symptoms) to 10 (had to stop exercise). Guidelines were given to participants prior to tests and during familiarisation/pilot work to make the differentiation between symptoms easier; HISI was recorded during the last minute of the HSTs.

Sleep deprivation protocol

A 7-day sleep diary was self-reported by the participants in the week prior to testing to assess average sleep (hours) and to ensure participants were not banking sleep. Participants were asked to complete the diaries in the morning after first waking and reported: time they went to bed, total hours slept and quality of sleep. Participants reported to the laboratories at 22:00, having been awake 14 h, to remain awake for the entirety of the night prior to testing at 08:00 (awake 24 h). Participants were continuously monitored and allowed to consume snacks and non-caffeinated beverages, each of which was recorded (Hom et al., 2012). This sleep deprivation protocol ensured participants remained in an energy-balanced state. The calorie content of food consumed was equal to average female calories (1348 ± 125 $kcal \cdot day^{-1}$) expended in the 10 h overnight due to sleep deprivation, ~562 kcal (Arciero, Goran, & Poehlman, 1993).

Blood sampling and analysis

Prior to both HSTs (follicular phase) and on Day 20–22 (luteal phase) of the participants' self-reported menses, a resting 6 mL venous blood sample was drawn from the median cubical vein, and centrifuged in duplicate at 4400 rpm and 4°C for 10 min (5702 R centrifuge, Eppendorf UK Ltd.). Plasma was then pipetted into 1.5 mL micro tubes (Western laboratory science, UK) and stored at −86°C (VIP series, Sanyo Electric Biomedical Co Ltd., Japan) for later analysis. Following the manufacturer's guidelines, analysis involved the use of commercially available 17β-estradiol (ab108667) and progesterone (ab108670) immunoenzymatic assay kits (Abcam plc, UK). Incubation, including the required quality control standards, was performed on an orbital platform shaker (Titramax 1000, Heidolp UK) at 1.5 mm vibration and read by a microplate reader using absorption at 450 nm (elx800, BioTek UK). As described by the manufacturer, the intra-assay and inter-assay variability was 9% and 10% for 17β-estradiol and 4% and 9.3% for progesterone, respectively. Moreover, the lowest detectable concentration of 17β-estradiol and progesterone was 20.26 and 0.24 $ng \cdot mL^{-1}$, respectively.

Statistical analyses

All data were analysed using a standard statistical package (SPSS version 20.0), and reported as mean ± SD. All data were analysed for normality using Shapiro–Wilk and for sphericity using the Greenhouse-Geisser method. As a measure of retest correlation, relative measures of intra class correlation (ICC) with 95% confidence intervals (CI) were calculated for the HISI scale at rest and during exercise, alongside Spearman's correlation (non-parametric data). Absolute measures of reliability were calculated using Bland–Altman limits of agreement (LOA) showing the mean bias and 95% CI; at rest, LOA = 0.38 (−0.64, 1.39), ICC = 0.918, and during exercise, LOA = 0.13 (−1.82,

2.07), ICC = 0.986. Non-parametric data sets; average and peak RPE, TS and HISI, were analysed using a Wilcoxon signed-rank test with Bonferroni correction applied. Paired samples *t*-tests were used for resting and end-test results. A 2-way (trial × time) repeated measures analysis of variance was completed for physiological measures. Effect size (*d*) was categorised as small (0.2), medium (0.5) and large (0.8) (Cohens, 1988). Statistical significance was accepted at the level of $P \leq 0.05$.

Results

Participant characteristics

Participants arrived to the laboratories for both main tests in a similar physiological resting state ($P > 0.05$) (Table 1) and completed the HST for both trials. Participants had a weekly average sleep of 7.50 ± 0.45 h per day and 7.20 ± 0.39 h prior to the first HST. No sleep occurred in the 24 h prior to SDHST with 375 ± 50 kcals consumed overnight to balance energy expenditure. Plasma concentrations of 17β-estradiol ($P = 0.48$) and progesterone ($P = 0.72$) were not different across the two main HSTs and higher on Day 20–22 of the self-reported menstrual cycle questionnaire (Table 1). None of the experimental sessions had to be withdrawn or repeated based on blood sample results.

Perception of HRI symptoms

The HISI score was significantly higher after sleep deprivation (HST 20 ± 16 vs. 28 ± 16 SDHST, $Z = -2.675$, $P = 0.01$) (Figure 1). The symptoms heat sensations on the head or neck, chills, stopping sweating and vomiting were not reported in either of the main trials by any of the participants. Percentage increases in the SDHST versus HST for the other nine symptoms varied from 15% to 50%. The largest increases following sleep deprivation occurred in nausea (50%), lightheaded (47%) and confusion (45%). The most commonly reported two symptoms for all participants reported were feeling tired and thirst, highlighted in Figure 2.

Physiological responses

Peak T_{re} was not different ($P = 0.22$, $d = 0.05$) between SDHST (39.35 ± 0.33°C) and HST (39.40 ± 0.35°C). No difference ($P = 0.81$, $d = 0.1$) was found in the ΔT_{re} as displayed in Figure 3. There was no difference between the two HSTs for any physiological variable, except average HR (HST 182 ± 7 vs. SDHST 180 ± 7 beats · min^{-1}, $d = 0.44$, $P = 0.01$) (Table 2).

Table 1. Participants resting characteristics before main heat stress tests (mean ± SD).

	HST	SDHST	Day 20
Resting HR (beats · min^{-1})	66 ± 7	64 ± 8	–
T_{re} (°C)	37.49 ± 0.20	37.42 ± 0.12	–
Pre NBM (kg)	63.5 ± 10.8	63.1 ± 10.7	–
U_{osm} (mOsm · kg^{-1} H_2O)	149 ± 90	132 ± 62	–
U_{sg}	1.003 ± 0.002	1.002 ± 0.001	–
HISI	1 ± 2	1 ± 3	–
Progesterone (pg · mL^{-1})	0.87 ± 0.31	0.66 ± 0.39	12.69 ± 8.24
17β-estradiol (pg · mL^{-1})	32.66 ± 8.36	34.78 ± 13.56	75.00 ± 37.22

Resting HR = heart rate, T_{re} = core temperature, Pre NBM = pre nude body mass, U_{osm} = urine osmolality, U_{sg} = urine specific gravity, HISI = heat illness symptom index resting value.

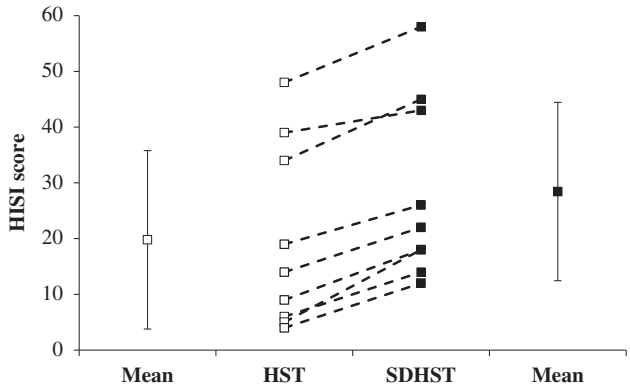

Figure 1. Heat illness symptom index (HISI) scores for the heat stress test (HST) and sleep deprived HST (SDHST) for each individual participant. Mean and SD also represented for HST and SDHST.

Correlational analysis

Spearman's correlation coefficient indicated a non-significant medium-positive trend, between change in T_{re} and end HISI score ($r = 0.58$, $P = 0.11$). This was also the case for peak T_{re} and end HISI score ($r = 0.44$, $P = 0.24$).

Discussion

The aim of this study was to determine if acute sleep deprivation would exacerbate the symptoms associated with HRI in females. The main findings revealed that sleep deprivation increased the perceptual symptoms associated with a HRI as presented by a greater HISI score, in line with the aforementioned hypothesis. Contrary to our second hypothesis, there were no differences in the rate of T_{re} rise following sleep deprivation. The primary variable investigated in this study was the HISI scale, a novel quantitative measurement of heat-related illness symptoms (Coris et al., 2006). Mean HISI score increased by 30% following sleep deprivation.

There is no existing literature assessing the HISI scale whilst exercising in the heat or sleep deprived, except the original Coris et al. (2006) study, which can offer comparison. They found correlations in HISI score with football training intensity, ambient temperature and fluid loss as a relationship for HRI. However, Coris et al. (2006) did not correlate HISI to T_{re} which might indicate the contribution core temperature has towards HISI symptoms and as a result HRI. In the current study however, we found a non-significant, but medium positive correlation between end T_{re} ($r = 0.44$) and ΔT_{re} ($r = 0.58$), and HISI score; potentially highlighting an association, but not a causal relationship between perceptual symptoms and physiological contributors to HRI. Figure 3 highlights the differences in symptoms of the HISI occurred for the nine participants over the two HSTs, where the two most commonly reported symptoms were "feeling tired" and "thirst". It is commonly accepted that the risk of HRI is directly influenced by dehydration (Coris et al., 2006). All participants were hydrated as a control measure prior to the 30 min run, and so the feeling of thirst is a perceptual indicator

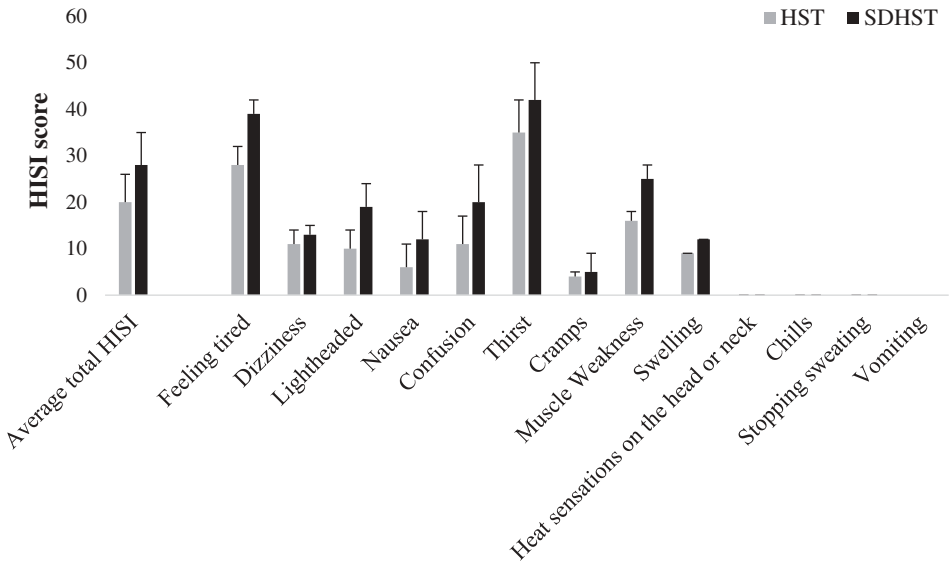

Figure 2. Each heat illness symptom index (HISI) symptom reported for all participants comparing both heat stress tests (mean ± SD).

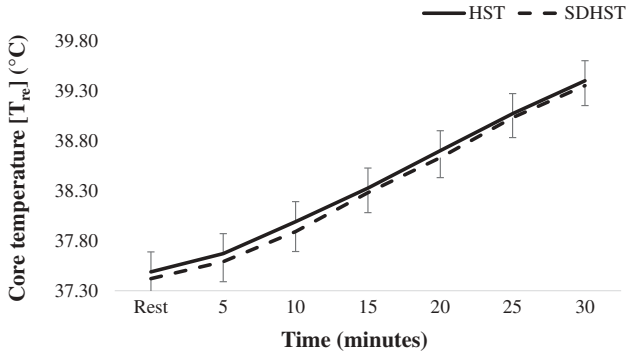

Figure 3. The time course of core temperature (T_{re}) (°C) during both heat stress tests: HST and SDHST. Data presented in mean ± SD.

of an enhanced risk of potential HRI. No participant reported "stopping sweating", which is a symptom primarily associated with heat stroke, an uncommon condition not reflective of mild HRI, reflected in the data (Coris et al., 2006). The largest increases following sleep deprivation compared to the HST were found in the symptoms nausea (50%), lightheaded (47%) and confusion (45%), highlighting the presence of some level of cognitive dysfunction, which is associated with heat exhaustion/stroke (Heled et al., 2004).

Literature surrounding the influence of sleep deprivation on T_{re} changes is equivocal (Fullagar et al., 2015). The current study concludes no difference in resting or peak T_{re}, in line with other literature (Fujita et al., 2003; Moore, Harper Smith, Di Felice, & Walsh, 2013; Muginshtein-Simkovitch et al., 2015; Oliver et al., 2009). Conversely, resting T_{re} may be lower following sleep deprivation of greater durations (Sawka et al., 1984); possibly indicating that sleep deprivation of <30 h may not be sufficient to induce alterations in thermoregulation. Mechanisms associated with these alterations to thermoregulation have been proposed to be due to an altered central nervous system function or changes in peripheral input (Moore et al., 2013); however, findings remain inconclusive.

Our study revealed no difference in RPE at any time point between HST and SDHST, in line with other studies (Moore et al.,

Table 2. Peak and average values represented as mean ± SD across both heat stress tests (HST).

	HST	SDHST	*P*	*t*-Value	*z*-Value
Peak T_{re} (°C)	39.40 ± 0.35	39.35 ± 0.33	0.22	1.40	
ΔT_{re} (°C)	1.91 ± 0.21	1.93 ± 0.34	0.81	−0.24	
Peak T_{skin} (°C)	37.43 ± 0.72	37.56 ± 0.92	0.12	−0.10	
Peak HR (beats · min^{-1})	192 ± 7	192 ± 7	0.3	−1.11	
Av HR (beats · min^{-1})	182 ± 7	180 ± 7	0.01*	3.70	
Peak TS	8.0 ± 0.5	8.0 ± 0.5	0.66		−0.45
Av TS	6.5 ± 0.5	6.5 ± 0.5	0.59		−0.53
Peak RPE	18 ± 2	18 ± 1	0.32		−1.00
Av RPE	15 ± 1	15 ± 1	0.29		−1.06
Sweat rate (L · h^{-1})	1.08 ± 0.31	1.15 ± 0.36	0.42	−0.84	
Av $\dot{H}_{prod}$ (W · kg^{-1})	9.8 ± 0.5	9.7 ± 0.4	0.67	0.44	

T_{re} = core temperature, T_{skin} = mean skin temperature, HR = heart rate, TS = thermal sensation, RPE = ratings of perceived exertion, Av $\dot{H}_{prod}$ = average heat production.
* indicates statistical significance between tests.

2013; Oliver et al., 2009). Although, previous literature suggested an increased perception of effort when exercising at fixed exercise intensities (Muginshtein-Simkovitch et al., 2015), a possible explanation for this discrepancy in our findings is interpreted to be exercise intensity-dependent. The methodology of Muginshtein-Simkovitch et al. (2015) consisted of low exercise intensity walking (5 km · h^{-1} at 2% gradient), whereas the other two studies (Moore et al., 2013; Oliver et al., 2009) and the current study required participants to run at a considerably higher exercise intensity (70% $\dot{V}O_2$max, self-paced treadmill run and at 10 W · kg^{-1} [77% $\dot{V}O_2$peak]). While thermal strain has been proposed to have a direct influence on subjective feelings (Sawka et al., 1984), in the current study TS did not differ between trials. These findings are in line with Moore et al. (2013) following partial sleep deprivation (PSD) (6 h over 3 days), although it has been reported that 24 h sleep deprivation heightened thermal comfort rating compared to PSD and non-sleep deprived tests under the same heat stress (40°C, 40% RH) (Muginshtein-Simkovitch et al., 2015). This highlights a potential issue with the sensitivity of the TS scale utilised in the current study, as participants' peak TS was 8.0 ± 0.5 in both tests, the maximum score achieved in just 30 min running. It has been previously stated that T_{skin} is the driver for TS (Schlader, Simmons, Stannard, & Mündel, 2011), reinforced by the findings of this study which indicated no differences in exercising or peak T_{skin} with no differences observed in TS. These conflicting results surrounding perception and sleep deprivation have been attributed to a large variation in sleep deprivation durations, exogenous factors of the experimental design (e.g., duration and intensity of exercise, temperature and humidity of environment) and a vast array of effects on emotional regulation (e.g., mood) following sleep deprivation (Fullagar et al., 2015).

Previous literature has suggested sleep deprivation (33 h) decreases sudomotor function (−27% sweat rate) (Sawka et al., 1984) induced by a reduction in reflex cutaneous vasodilation and peripheral blood flow (Kolka & Stephenson, 1988). An explanation of this alteration is due to participants exercising at relative exercise intensities evoking different heat productions and evaporative heat loss requirements as a consequence of the experimental protocol (Cramer & Jay, 2014). In contrast, there were no difference in whole body sweat rate in the current study (Table 2), similar to the findings by Moore et al. (2013), who demonstrated PSD to have no effect on sweat rate (1.30 ± 0.41 vs. 1.26 ± 0.4 L · h^{-1} [PSD]). Hom et al. (2012) reported an increased sweat rate after 28 h sleep deprivation, although this followed 10 days heat acclimation where improved sudomotor function is likely attributed to heat adaptation not sleep deprivation. Sudomotor responses are primarily initiated by increased T_{re} and T_{skin} (Kolka & Stephenson, 1988), though human abdominal receptors may also be relevant (Morris, Coombs, & Jay, 2016) and contribute to the afferent neural signals integrated at the hypothalamus (Shibasaki, Wilson, & Crandall, 2006). T_{re} and T_{skin} did not differ between conditions and as expected, no difference in sweat rate occurred (Table 2). In light of this, controlling for the factors that alter thermoregulatory responses in this study (e.g., circadian rhythm, hydration status, $\dot{H}_{prod,}$ menstrual cycle) (Sawka et al., 2007), it is suggested sleep deprivation does not alter sudomotor function during an acute bout of exercise-heat stress in females.

It has been proposed that sleep deprivation may compromise cardiovascular regulation, primarily associated with a reduced sympathetic activity; however, there is also research that has reported HR to decrease or be unchanged following sleep deprivation (Oliver et al., 2009; Sawka et al., 1984). The current study found a significantly reduced exercising HR following SDHST (−2 ± 6 beats · min^{-1}, P = 0.01). However, other studies have reported larger, more meaningful reductions (Muginshtein-Simkovitch et al., 2015; Vaara, Kyröläinen, Koivu, Tulppo, & Finni, 2009). This is emphasised by only a small effect found in the current study for this 2 beats · min^{-1} reduction (d = 0.44). A downregulated sympathetic cardiac autonomic activity, increased vagal outflow after 30 and 60 h sleep deprivation has been shown (Vaara et al., 2009); while HR is reported to reduce with chronic sleep deprivation, shorter acute periods do not induce meaningful cardiovascular reductions.

Limitations and future recommendations

As sleep was evaluated using self-reported diaries (Carney et al., 2012), it is recommended that these are validated alongside a quantitative method for analysing sleep data (e.g., actigraphs), as seen in previous literature (Muginshtein-Simkovitch et al., 2015). Results from this study follow the controls aforementioned and are constrained to females in the follicular phase of the menstrual cycle (Stachenfeld & Taylor, 2014), reinforced in Table 1. During the luteal phase, progesterone concentrations are elevated (~10 ng · mL^{-1}) increasing resting T_{re} by ~0.3–0.6°C, onset threshold for cutaneous vasodilation by 0.2–0.3°C and sweating threshold by 0.3°C (Pivarnik et al., 1992). It would therefore be of interest to conduct testing in the luteal phase to offer comparison and investigate how the different phases of the menstrual cycle may affect how females respond in the heat when sleep deprived. As highlighted by Coris et al. (2006), the main limiting factor was that HISI scores were not correlated to a physiological measure. It is reported in the literature that a higher T_{re} contribute to HRI and be associated with more extreme heat illnesses (e.g., heat stroke) (Moran et al., 2004). Therefore, assuming this correlation exists, a higher T_{re} should ensure a higher reported HISI score; however, empirical evidence is still required. As such, future research allied to the HISI should focus on identifying the association of symptom with T_{re} and adjust the index accordingly. The highest score reached was 58, under half of the potential maximum (130), where the participants were reaching near maximal HR (≥180 beats · min^{-1}) and high T_{re} (≥39.2°C). Therefore, the validity and sensitivity of the HISI require further examination during high-intensity exercise, passive heat exposures and long-term interventions (e.g., heat acclimation). Further multidisciplinary research is required to determine how acute, intermittent and prolonged sleep deprivation disrupts cognition and how it may alter aerobic or occupational performance under heat stress, especially for athletic or military individuals where perception, pacing and decision-making are critical.

Conclusion

This is the first study investigating acute sleep deprivation while controlling for individual alterations to a stressor accurately through $\dot{H}_{prod}$, under uncompensable heat stress. It was reported that 24 h sleep deprivation increased the perception of symptoms related to HRI but had no effect on

thermoregulatory function. These novel findings emphasise that contrary to previous literature, younger (<30 years) female athletes, occupational workers or military personnel, who experience an acute bout of 24 h sleep deprivation during shift work or travelling to a hot climate, will not incur an enhanced physiological strain during high-intensity exercise.

Acknowledgements

The author would like to thank the volunteers for their participation in this investigation, as well as Aimee Jones, Claire Carroll and Emily Watkins for their assistance in data collection.

Conflict of Interest

The authors declare that they have no competing interests such as funding or personal financial interest.

Disclosure statement

No potential conflict of interest was reported by the authors.

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