Short-term sleep deprivation and human thermoregulatory function during thermal challenges

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1 INTRODUCTION

Human temperature regulation is achieved through the seamless recruitment of autonomic and behavioural thermoeffectors, aiming to maintain body core temperature ($T_c$) within a relatively narrow range (i.e., $\sim 37 \pm 0.5$°C; Bligh, 1998; Taylor & Gordon, 2019). Thus, in a thermally stressful environment, modulations in peripheral vasomotor tone regulate the rate of dry heat loss, whereas cutaneous sudomotion regulates evaporative heat loss, and muscular shivering, and in part non-shivering processes, enhance heat production. Also, conscious behavioural interventions (e.g., changes in clothing, use of electrical fan) intend to establish a thermally comfortable (micro)environment, promoting heat balance. The inability of any of these thermoregulatory effector mechanisms to preserve body thermal equilibrium leads to hypo- or hyperthermia, which can degrade cognitive and physical performance and, in some instances, can be life threatening. Aside from thermal influences, thermoregulatory function is also subject to non-thermal stressors (e.g., exercise, malnutrition, dehydration), which, in an interactive manner, may alter the threshold for and/or the gain (sensitivity) of thermoeffector(s), and further jeopardize the capacity to maintain thermal balance (Kenny & Journeay, 2010; Mekjavic & Eiken, 2006). Such non-thermal stressors may act on different components of the thermoregulatory control system; that is, they might modulate the sensory transduction in thermoreceptors, the conveyance of the afferent information, its integration in the CNS and/or the activity of the effector end-organs.

Sleep is regarded crucial for retaining physiological and psychological function. Shift-workers, military and emergency-response (e.g., firefighters, rescuers) personnel and ultra-endurance athletes are often required to perform in adverse thermal conditions, while in a state of prolonged wakefulness. A large body of human-based studies has yielded evidence that sleep deprivation, whether total (TSD; complete sleep abstinence for $\geq 24$ h) or partial (PSD; total sleep duration, continuous or fragmented, $< 5$ h day$^{-1}$), induces...
physiological and psychological perturbations, which in turn provoke negative effects (e.g., depression, anger, confusion), aggravate perceived fatigue, impair cognitive function (e.g., alertness, logical reasoning, decision-making, vigilance, executive function) and, typically, deteriorate physical capacity (for reviews, see Fullagar et al., 2015; Grandou et al., 2019; Killgore, 2010; Lowe et al., 2017). Considering the essential role of sleep in the regulation of the milieu intérieur, its potential restorative function (see Frank & Benington, 2006), and the close interrelationship of sleep with the thermoregulatory system (see Krauchi & Deboer, 2010), it is reasonable to assume that sleep deficit might also disturb thermal homeostasis, enhancing susceptibility to cold- [i.e., (non-)freezing cold injury and hypothermia] and heat-related (i.e., heat exhaustion and heatstroke) illnesses. Such a notion seems to be supported by anecdotal field-based observations (Pugh, 1966; Rav-Acha et al., 2004; Young et al., 1998); and thus, sleep deprivation has conventionally been suggested to be a predisposing factor to the development of thermal injury (Armstrong et al., 2007; Casa et al., 2012; Castellani et al., 2006; Rintamaki, 2000). Nonetheless, the findings derived from original experimental investigations, wherein the confounding influence of other non-thermal stressors (e.g., physical exertion, caloric deficit) on thermoregulation has been eliminated, appear to be ambiguous.

The purpose of this brief narrative review, therefore, is to summarize the available evidence on the effects of sleep loss on autonomic and behavioural thermoeffectors during acute exposure to low and high ambient temperatures. Our literature search was limited to healthy human populations and to studies evaluating resting and exercise thermoregulation after relatively short periods (i.e., ≤4 nights) of experimentally induced sleep deprivation.

2 | SLEEP DEPRIVATION AND AUTONOMIC THERMOEFFECTORS

2.1 | Thermoregulation in response to cold

During cold stress, thermal homeostasis is preserved via a sympathetically mediated increase in peripheral vasomotor tone, attenuating heat loss to the surroundings, and the activation of muscle shivering and, to a small extent, of non-shivering thermogenesis. Yet, during sustained cold exposure, protracted peripheral vasoconstriction can lead to local cold injury, especially in the acral skin regions (i.e., finger, toe, nose). Also, when the rate of endogenous heat production fails to offset the rate of body heat loss, hypothermia can eventuate.

Military-based studies have demonstrated that periods of sustained operations, during which TSD or PSD is commonly encountered, may compromise thermoregulation to cold, enhancing the risk of hypothermia. Thus, a substantial long-term (61 days) sustained operation blunted shivering thermogenesis and cutaneous vasoconstriction, and accelerated body core cooling during a 4 h cold (10°C) air exposure (Young et al., 1998). In line with this, Castellani et al. (2003) found that even a relatively short (84 h) sustained operation with PSD attenuated the thermogenic response to acute cold (10°C air), because of a delay in the shivering onset threshold. However, during these strenuous military exercises, individuals, along with being sleep deprived, are often exposed to other behavioural stressors, such as physical and mental exertion and caloric deficit, which, independently or interactively, might impinge on the thermoregulatory system. For instance, sustained periods of underfeeding (Macdonald et al., 1984), as well as fatigue engendered by prolonged and exhaustive exercise (Castellani et al., 1999, 2001), appear to impair the reflex vasoconstrictor response to cold, whereas hypoglycaemia can inhibit shivering thermogenesis (Gale et al., 1981; Passias et al., 1996), thereby potentiating the reduction in body $T_c$. Lastly, morphological alterations are also caused by such multistressor regimes; reductions in body lean and fat mass often ensue (Young et al., 1998), degrading the insulative capacity (Cannon & Keatinge, 1960).

The distinct effects of short-term TSD on thermoeffector responses to whole-body cold exposure have been examined in eight independent studies, of which only two have indicated that the cold-defence effectors are modified by TSD (Table 1). Firstly, Landis et al. (1998) noted that, in sleep-deprived women, the reduction in body $T_c$ was slightly accelerated during brief intervals of mild skin cooling [skin temperature ($T_{sk}$) was deliberately fluctuated and clamped from 38 to 32°C]. However, the mechanisms underlyng this response are unclear; the cold-induced changes in non-glabrous (forearm) skin blood flow were unaltered by TSD, whereas the endogenous production of heat was not monitored. Secondly, Savourey and Bittel (1994) observed in men that a 27 h TSD might compromise the heat-conservation mechanisms, as reflected by higher $T_{sk}$ values obtained during a 2 h exposure to 1°C air. Nevertheless, TSD elicited a robust metabolic

New Findings

- What is the topic of this review?
  It is generally accepted that sleep deprivation constitutes a predisposing factor to the development of thermal injury. This review summarizes the available human-based evidence on the impact of sleep loss on autonomic and behavioural thermoeffectors during acute exposure to low and high ambient temperatures.

- What advances does it highlight?
  Limited to moderate evidence suggests that sleep deprivation per se impairs thermoregulatory defence mechanisms during exposure to thermal extremes. Future research is required to establish whether inadequate sleep enhances the risk for cold- and heat-related illnesses.
### Table 1
Summary of the experimental studies that have investigated the impact of short-term (\(\leq 4\) nights) sleep deprivation on human thermoregulation during whole-body or local cold exposure

| Study                      | N   | Sleep deprivation protocol | Thermal provocation                           | Responses during the thermal provocation | Behavioural thermoeffectors (including perceptual responses) | Other physiological responses |
|----------------------------|-----|----------------------------|-----------------------------------------------|------------------------------------------|---------------------------------------------------------------|-------------------------------|
| Fiorica et al. (1968)      | 12♂ | 6 TSD vs. 6 control        | 1°C air for 60 min                            | ↓ (rectum)                              | ∅ Tsk ∅ M                                                   | ∅ HR ∅ catecholamines          |
| Kolka et al. (1984)        | 7(6♂,1♀) | 50 h of TSD           | 0°C air: treadmill walk (speed, 1.56 m s\(^{-1}\); freely chosen gradient and duration) | ∅ (rectum)                              | ∅ Tsk ∅ M                                                   | ∅ self-selected gradient ∅ exercise duration ∅ displeasure ∅ HR |
| Savourey and Bittel (1994) | 12♀ | 27 h of TSD              | 1°C air for 120 min                           | ∅ (rectum)                              | ↑ Tsk ↑ \(\dot{M}\)                                          | n.a.                           |
| Landis et al. (1998)       | 6♀  | 1 night of TSD           | 2× Tsk clamped at 32 and 38°C for 10–20 min   | ↑ cooling rate (oesophagus)              | ∅ forearm SkBF                                               | ∅ HR                           |
| Caine-Bish et al. (2004)   | 12(6♂,6♀) | 33 h of TSD            | 12°C air for 180 min                          | ∅ (rectum)                              | ∅ Tsk ∅ M                                                   | n.a.                           |
| Costa et al. (2010)        | 10♀ | 53 h of TSD with or without energy restriction | 0°C air until \(T_c \leq 36°C\)              | ∅ (rectum)                              | n.a.                                                         | ∅ thermal discomfort ∅ thermal pain ∅ HR ∅ immune indices |
| Esmat et al. (2012)        | 8♀  | 53 h of TSD              | 10°C air for 120 min → 120 min passive rewarming | ∅ (rectum)                              | ∅ Tsk ∅ M                                                   | ∅ thermal sensation n.a.       |
| Sauvet et al. (2012)       | 10♀ | 29 h of TSD              | Immersion of right hand in 5°C water for 30 min→30 min spontaneous rewarming | ∅ (rectum)                              | ↓ finger Tsk ↓ finger SkBF ↓ finger CIVD                    | Slightly ↑ thermal pain        |
| Oliver et al. (2015)       | 10♀ | 53 h of TSD with or without energy restriction | 0°C air for 240 min or until \(T_c \leq 36°C\) | ∅ (rectum)                              | ∅ Tsk ∅ M                                                   | ∅ thermal discomfort ∅ thermal pain ∅ HR ∅ plasmaglucose, catecholamines |

The studies are reported in chronological order. Note that the responses describe differences from the respective control conditions (i.e., normal nocturnal sleep). Abbreviations: AP, arterial pressure; CIVD, cold-induced vasodilatation; HR, heart rate; N, total number of participants; \(\dot{M}\), metabolic heat production; n.a., information not available; SkBF, skin blood flow; \(T_c\), body core temperature; TSD, total sleep deprivation; \(T_{sk}\), skin temperature; ♂, male participants; ♀, female participants; ∅, no difference; ↑, increase; ↓, decrease.
response to cold and hastened the threshold onset for shivering, which apparently compensated for the increased rate of heat loss, hence obviating a potentiation of hypothermia after TSD.

Contrary to the aforementioned two studies, the others have failed to detect any adverse effects of TSD on thermoregulation to cold, during both resting conditions (Caine-Bish et al., 2004; Costa et al., 2010; Fiorica et al., 1968; Oliver et al., 2015) and moderate-intensity exercise (Kolka et al., 1984). Of interest is the work of Oliver et al. (2015) and Costa et al. (2010), who, by using a within-subject design, found that 53 h of TSD combined with or without negative energy balance neither perturbed thermoeffector capacities (Oliver et al., 2015) nor modulated the immune reactions (the suppression of circulating lymphocytes, neutrophil degranulation and saliva secretory immunoglobulin A) evoked by acute cold (0°C air) stress (Costa et al., 2010). Lastly, the rewarming response after a period of whole-body cooling does not appear to be disturbed by TSD (Esmat et al., 2012; Oliver et al., 2015).

Sleep deprivation has also been regarded as a factor predisposing to the development of local cold injury (Rintamaki, 2000). Indeed, 29 h of TSD augmented finger vasoconstriction instigated by a 30 min direct localized cooling (5°C water) and delayed the spontaneous rewarming of the extremity after this cooling (Sauvet et al., 2012). The response was attributable to a TSD-dependent microvascular endothelial dysfunction (for review, see Cherubini et al., 2021), characterized mainly by increased concentrations of endothelin 1 (a potent vasoconstrictor) and perhaps by reduced concentrations of nitric oxide (a potent vasodilator) (Sauvet et al., 2010, 2012, 2017). The lack of sleep, however, did not modify the incidence or the magnitude (i.e., onset and amplitude) of finger cold-induced vasodilatation (aka CIVD), which typically intervenes during cooling of the hands and/or feet (Keramidas et al., 2019) and, presumably, serves a cryoprotective function against cold injury (Wilson & Goldman, 1970).

Collectively, the prevailing evidence suggest that, during whole-body mild cold stress, short-term TSD does not exert any prominent influence on the function of autonomic thermoeffectors; therefore, further work is required to establish whether inadequate sleep per se potentiates the risk of hypothermia. Sleep deprivation, however, might represent a contributing factor for the development of freezing and non-freezing cold injury, given that, on the basis of a single study (Sauvet et al., 2012), the acral skin constrictor responsiveness to localized cooling is aggravated by TSD.

2.2 Thermoregulation in response to heat

During heat stress, thermal homeostasis is maintained through peripheral vasodilatation and sweating, which respectively facilitate the dry and evaporative heat transfer from the body to the environment. However, when the capacity to dissipate heat is limited (e.g., in hot and humid conditions or while wearing personal protective clothing and equipment), especially during exercise, the resultant sustained increases in body heat storage augment the \( T_c \) elevation, which in turn degrades performance and can eventually lead to the development of heat-related illnesses, such as heat exhaustion and heatstroke.

It is generally accepted that sustained periods of wakefulness disturb exercise thermoregulation and thus increase the risk of exertional heat illness (Armstrong et al., 2007; Casa et al., 2012). Seminal work by Sawka et al. (1984) showed that, in aerobically fit men, TSD (33 h) suppresses dry and evaporative heat loss during sub-maximal whole-body exercise performed in thermally compensable conditions (28°C, 30% relative humidity). This early observation was corroborated by two later studies that evaluated the impact of TSD, with a duration similar to that in the study by Sawka et al. (1984), on exercise thermoregulation during exposure to hot (35°C) ambient conditions (i.e., in thermally uncompensable state). Namely, Kolka and Stephenson (1988) demonstrated that the regional (forearm) dry heat exchange was impaired; furthermore, Dewasmes et al. (1993), who clamped the local (chest and thigh) \( T_{ec} \) at 35.5°C, found that the secretion of sweat in these regions was reduced. Ergo these studies demonstrated that TSD modulates peripheral heat loss during exercise provocations. Nevertheless, the origin of this thermoregulatory response remains unsettled. It has been attributed either to a peripheral desensitization, judging by the reduction in the gain of heat-loss effectors (Kolka & Stephenson, 1988; Sawka et al., 1984) and/or to a centrally mediated delay in the activation threshold for heat dissipation (Dewasmes et al., 1993; Kolka & Stephenson, 1988). However, and regardless of the exact mechanism, it is noteworthy that, apart from work by Sawka et al. (1984), wherein a tendency for a slightly greater increase in body \( T_c \) (−0.2°C) was noted after TSD, the blunted responsiveness of the monitored regional (non-glabrous) heat-dissipation pathways did not lead to significant heat gains, and therefore, the exercise-induced elevations of internal body temperature were not augmented by TSD (Dewasmes et al., 1993; Kolka & Stephenson, 1988).

Considering the large inter-regional variation in cutaneous vasomotion (Caldwell et al., 2014, 2016) and sweat production (Cramer et al., 2012; Machado-Moreira & Taylor, 2017), it is not known whether the glabrous skin areas (e.g., forehead) responded in a different manner from the non-glabrous sites after TSD.

The results from the aforementioned exercise-based investigations appear to concur, in part, with those of studies that examined the influence of TSD on thermoregulation during passive heat stress (Table 2). For instance, during a brief period of mild (38°C) whole-body skin heating, the magnitude of forearm vasodilatation was attenuated in sleep-deprived women, but the rates of change in sweating and body \( T_c \) remained unaltered (Landis et al., 1998). Moreover, Fujita et al. (2003) noted that, during a 60 min whole-body exposure to 30°C air and while the lower legs were immersed in 42°C water, the total sweat loss (indicated by the changes in body weight) was impaired by TSD; however, the increases in regional dry heat loss (reflected by an increase in back and forearm skin blood flow) and body \( T_c \) were potentiated and diminished, respectively. In addition, after 36 h of TSD, the body \( T_c \) elevation during iterative exposures to severe (sauna) heat stress (four bouts of 10–15 min at 80–90°C, 30% relative
| Study                        | N  | Sleep deprivation protocol | Thermal provocation | Responses during the thermal provocation | Behavioural thermoeffectors (including perceptual responses) | Other physiological responses |
|------------------------------|----|----------------------------|---------------------|------------------------------------------|-------------------------------------------------------------|-----------------------------|
| Sawka et al. (1984)          | 5♂  | 33 h of TSD                | 28°C, 30% RH; 40 min cycling at 50% of $V_{O_{2peak}}$ | ↑ $T_{sk}$; not significant (oesophagus) | n.a.                                                         | ⊙ HR                         |
| Kolka and Stephenson (1988)  | 6 (3 ♂, 3 ♀) | 33 h of TSD | 35°C; 30 min cycling at 60% of $V_{O_{2peak}}$ | ⊙ (oesophagus) | n.a.                                                         | n.a.                         |
| Dewasmes et al. (1993)       | 5♂  | 27 h of TSD                | 35°C; 45 min cycling at ~50% of $V_{O_{2peak}}$ (chest and thigh $T_{sk}$ clamped at 35.5°C) | ⊙ (oesophagus) | n.a.                                                         | ⊙ HR                         |
| Landis et al. (1998)         | 6♀  | 1 night of TSD             | 2 × $T_{sk}$ clamped at 32 and 38°C for 10–20 min | ⊙ threshold for sweating | ⊙ thermal sensation, ⊙ thermal discomfort                  | ⊙ HR                         |
| Fujita et al. (2003)         | 8♂  | 1 night of TSD             | Whole body in 30°C, 70% RH, lower legs in 42°C water for 60 min | ↓ (rectum) | ⊙ $T_{sk}$; ⊙ back and forearm SkBF; ⊙ $V_{O_{2}}$; ⊙ SwR | n.a.                         |
| Moore et al. (2015)          | 10♂ | 3 days of PSD (~116 min of sleep per night) | 33°C, 40% RH; 45 min running at 70% of $V_{O_{2peak}}$ | ⊙ (rectum) | ⊙ $T_{sk}$; ⊙ total SwR                                  | ⊙ perceived effort           |
| Muginshtein-Simkovitch et al. (2015) | 11♂ | 24 h of PSD (~5 h of sleep) | 40°C, 40% RH; 120 min treadmill walk (5 km h⁻¹, 2% inclination) | ⊙ (n.a.) | ⊙ $V_{O_{2}}$; ⊙ SwR                                  | ⊙ perceived effort           |
| Tokizawa et al. (2015)       | 14♂ | 24 h of PSD (~4 h of sleep) | 35°C, 40% RH: 2 × 40 min treadmill walk (at 3.5 km h⁻¹) → 30 min nap or no nap → 2 × 40 min treadmill walk (at 3.5 km h⁻¹) | ↑ $T_{sk}$ in the afternoon trials (rectum) | ⊙ thermal sensation in the afternoon trials; ⊙ SwR in the afternoon trials | ⊙ HR                         |

(Continues)
The negative influence of TSD on autonomic thermoeffectors during exercise is not a ubiquitous finding, however (Table 2). Relf et al. (2018) used a closed-loop exercise protocol, during which nine young women ran, before and after a sleepless night, for 30 min at fixed (clamped) metabolic heat-production rates (10 W kg⁻¹) at 39°C (41% relative humidity). Notably, neither sweating nor body \( T_c \) responses were influenced by TSD, but the prevalence of the self-reported symptoms associated with heat exhaustion, such as nausea, lightheadedness and confusion, was aggravated (see next section). Likewise, Muginshtein-Simkovitch et al. (2015) found in well-trained men that, although the perceived thermal comfort was compounded, the exercise-induced thermal strain at 40°C (40% relative humidity) was not amplified by 24 h of TSD. These authors, however, argued that the magnitude of the TSD response might be dependent on the individual chronotype; that is, people with an evening chronotype are more vulnerable than others. Nevertheless, this assumption emanated from a very small sample size (three evening chronotypes vs. eight intermediate chronotypes) and needs to be justified by further experiments. Lastly, there is a sole indication (Hom et al., 2012) that one night of TSD did not disturb the thermo-adaptive modifications evoked by repeated heat exposures; adjustments that were described by enhanced sweating rates and lower increases in \( T_c \) during exercise.

With regard to the impact of PSD, relatively short periods of sleep restriction (1–4 nights; 4–5 h sleep per night) ostensibly do not impose a potent risk for thermoregulatory dysfunction during heat stress (Cernych et al., 2021; Muginshtein-Simkovitch et al., 2015; Tokizawa et al., 2015). Of note, however, is the work by Tokizawa et al. (2015) showing that, although a night of PSD (4 h of sleep) did not perturb temperature regulation during morning exercise, it exacerbated the exercise-induced elevation in body \( T_c \) during successive exercise bouts performed during the same afternoon (ambient conditions: 35°C, 40% relative humidity). Whether this delayed response was attributable to the extended period of wakefulness and/or to the accumulated amounts of fatigue provoked by the preceded morning exercise remains unclear. Arguably, it could also be associated with a PSD-induced circadian dysregulation emerging in the afternoon trials; however, it should be noted that, although \( T_c \) and \( T_{sk} \) exhibit a distinct cyclic variation over a 24 h period (Aldemir et al., 2000; Aoki et al., 2001; Kräuchi & Wirz-Justice, 1994; Refinetti & Menaker, 1992), the sweating response to exercise in the heat does not appear to describe a circadian rhythmicity, at least in waking periods (Ravannell & Jay, 2020). Nevertheless, it is noteworthy that the enhanced degree of thermal strain noted in the afternoon trials was not counteracted or at least mitigated by a 30 min post-lunch nap that occurred between the morning and afternoon sessions.

Altogether, TSD might modify the efficiency of heat-dissipation effectors during compensable and uncompensable heat stress. There is no compelling evidence, however, that TSD potentiates hyperthermia during resting conditions or exercise. Also, ≤4 days of PSD do not seem to hinder the ability to thermoregulate in the heat.
3 SLEEP DEPRIVATION AND BEHAVIOURAL THERMOEFFECTORS

Thermoregulatory behaviour describes the deliberate actions, either simple or more complex, that aim to create a thermally comfortable (micro)environment. Examples of thermobehavioural means include, inter alia, changes in body position or clothes and adjustments of exercise intensity. These behavioural counteractions constitute the most powerful response to defend body $T_c$ from environmental thermal challenges (Hardy, 1971; Schlader & Vargas, 2019), and their utilization seems to prevent or at least postpone the recruitment of the energetically costly autonomic thermoeffectors (i.e., sweating and shivering) (Schlader et al., 2018). To our knowledge, only one study in humans has attempted to evaluate directly (i.e., in experimental conditions of behavioural freedom) whether the desire for and the magnitude of thermobehaviour are modulated by sustained periods of wakefulness. Namely, 50 h of TSD did not modify the self-paced exercise intensity and duration nor the thermal and perceptual (affective valence) strain while walking in 0°C air (Kolka et al., 1984).

The conscious behavioural interventions are motivated by adequate changes in thermal perception invoked by $T_{sk}$ and/or $T_c$ displacements (Gagge et al., 1967; Satinoff, 1996). Therefore, valuable insights into the impact of sleep deprivation on behavioural thermoregulation may be gained by the assessment of the self-reported discriminative (i.e., thermal sensation) and, especially, hedonic [i.e., thermal (dis)comfort] perceptions. Considering the recurrently described influence of sleep deficit on cognition (Killgore, 2010), it might be assumed that the thermoperceptual responsiveness to thermal stimuli would also be affected; however, the results on whole-body thermoperception after a period of sleep loss appear to be inconsistent (Tables 1 and 2). Thus, 53 h of TSD exacerbated thermal discomfort during the initial 1 h of a 4 h exposure to 0°C air; a response that was independent of any TSD-driven variation in the whole-body thermal state of subjects (Oliver et al., 2015). Such a thermoperceptual sensitization, however, is not supported by other cold-relevant studies (Costa et al., 2010; Esmat et al., 2012; Landis et al., 1998). Conflicting findings have also been obtained during whole-body heat stress. For instance, after a sleepless night, Muginshtein-Simkovitch et al. (2015) found that the subjective ratings for thermal discomfort and of effort perception were enhanced during moderate exercise performed at 40°C, whereas Reif et al. (2018) did not observe any modifications of the perceived thermal pleasantness while exercising at 39°C (in both studies, the relative humidity was ~40%). Nevertheless, in the latter study, the prevalence of self-reported symptoms associated with heat exhaustion (e.g., nausea, lightheadedness, confusion) was increased after TSD. Furthermore, after a night of PSD, the sensations of fatigue and hotness, but not of thermal discomfort, were aggravated during sub-maximal exercise in thermally uncompensable conditions (35°C, 40% relative humidity; Tokizawa et al., 2015). Of interest was that a 30 min nap interval, although failing to attenuate the thermal and cardiovascular strain encountered during exercise after TSD, did alleviate the PSD-evoked sensations (i.e., subjects felt less hot; Tokizawa et al., 2015). This nap-related thermoperceptual desensitization might, in fact, compromise behavioural thermoregulatory adjustments, presumably imposing a greater risk of heat exhaustion (cf. Moore et al., 2015). Lastly, there are indications that sleep deficit produces a hyperalgesic response to regional, noxious thermal stimuli; that is, the heat and cold pain thresholds might be accelerated after TSD (Kundermann et al., 2004). A 29 h period of sleep deprivation tended to augment the cold-induced pain during a 30 min hand immersion in 5°C water; a response that might have been determined by the enhanced degrees of finger vasoconstriction after TSD (Sauvet et al., 2012).

Collectively, information pertaining to the effects of sleep deprivation on human behavioural thermoregulation is lacking. Further work is also needed to elucidate whether the magnitude of thermoreceptive and thermonociceptive adaptations potentially induced by sleep deprivation would exert an influence on the decision-making to thermoregulate behaviourally.

4 CONCLUDING REMARKS

This brief review demonstrates that, in humans, a paucity of data exists concerning the distinct effects of relatively short periods (≤4 nights) of sleep deprivation on the function of autonomic and behavioural thermoeffectors. A few studies have provided some evidence that inadequate sleep might disturb thermal homeostasis (Figure 1); however, additional research is required to establish whether sleep loss constitutes a risk factor either causal or contributing to the development of thermal injuries. Accordingly, future investigations should evaluate this notion in a larger cohort, involving both male and female participants, use counterbalanced cross-over designs and, preferably, use ecologically valid protocols with respect to the sleep-deprivation treatments and the thermal provocations. In this context, the ability to thermoregulate after periods of sustained wakefulness needs to be assessed specifically under uncompensable thermal loads; for instance, during whole-body cold-water immersion (i.e., moderate to severe cold stress) and during prolonged and demanding work performed in hot and humid conditions while wearing protective clothing ensembles. Whether or to what extent sleep deprivation causes circadian dysregulation of thermoeffector capacity should also be determined. In this regard, the levels of melatonin, which modify skin circulation (Aoki et al., 2006, 2008) and are probably linked with the diurnal fluctuations in cutaneous vasomotor tone (Krauchi & Deboer, 2010), are enhanced by sleep deprivation (Salin-Pascual et al., 1988; Zeitger et al., 2007); nevertheless, the contribution of the sleep deprivation-induced changes in melatonin to human thermoregulation while in thermal extremes is not known. Studies should also seek to examine, in a well-controlled manner, the interaction of sleep deficit and other non-thermal stressors [e.g., (mal)nutrition, dehydration, physical exertion, altitude], conditions that are often encountered simultaneously in real-life settings, on temperature regulation. Lastly, the influence of behavioural countermeasures, commonly used to minimize the functional impairments caused by sleep deprivation...
(e.g., nap, sleep ‘banking’), on thermoregulation warrants further investigation.

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AUTHOR CONTRIBUTIONS
Both authors (M.E.K. and P.G.B.) designed and outlined the work, performed the literature review, interpreted findings and drafted and revised the manuscript. Both authors approved the final version of the article and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. Both persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

COMPETING INTERESTS
None declared.

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REFERENCES
Aldemir, H., Atkinson, G., Cable, T., Edwards, B., Waterhouse, J., & Reilly, T. (2000). A comparison of the immediate effects of moderate exercise in the late morning and late afternoon on core temperature and cutaneous thermoregulatory mechanisms. Chronobiology International, 17, 197–207.
Aoki, K., Stephens, D. P., & Johnson, J. M. (2001). Diurnal variation in cutaneous vasodilator and vasoconstrictor systems during heat stress.

FIGURE 1 A schematic overview of the possible effects of relatively short periods (i.e., ≤4 nights) of sleep deprivation on human thermoregulatory function during exposure to low and high ambient temperatures. The symbols indicate that the physiological/perceptual response of a sleep-deprived individual is increased (↑), decreased (↓) or does not differ (∅) relative to his/her response after normal nocturnal sleep, or that there is no available evidence (?). Abbreviations: AP, arterial pressure; CIVD, cold-induced vasodilatation; Q, cardiac output; SkBF, skin blood flow; SwR, sweating rate; Tc, body core temperature; Tsk, skin temperature; VO2, oxygen uptake. Note: the selection of male and female representations in the figure is random. Created with BioRender.com
American Journal of Physiology: Regulatory Integrative and Comparative Physiology, 281, R591–R595.
Aoki, K., Stephens, D. P., Zhao, K., Kosiba, W. A., & Johnson, J. M. (2006). Modification of cutaneous vasodilator response to heat stress by daytime exogenous melatonin administration. American Journal of Physiology. Regulatory Integrative and Comparative Physiology, 291, R619–R624.
Aoki, K., Zhao, K., Yamazaki, F., Sone, R., Alvarez, G. E., Kosiba, W. A., & Johnson, J. M. (2008). Exogenous melatonin administration modifies cutaneous vasconstrictor response to whole body skin cooling in humans. Journal of Pineal Research, 44, 141–148.
Armstrong, L. E., Casa, D. J., Millard-Stafford, M., Moran, D. S., Pyne, S. W., & Roberts, W. O. (2007). American College of Sports Medicine position stand. Exertional heat illness during training and competition. Medicine and Science in Sports and Exercise, 39, 556–572.
Bligh, J. (1998). Mammalian homeothermy: An integrative thesis. Journal of Thermal Biology, 23, 143–258.
Caine-Bish, N. L., Potkanowicz, E. S., Otterstetter, R., & Glickman, E. L. (2004). Thermal and metabolic responses of sleep deprivation of humans during acute cold exposure. Aviation Space and Environmental Medicine, 75, 964–968.
Caldwell, J. N., Matsuda-Nakamura, M., & Taylor, N. A. (2014). Three-dimensional interactions of mean body and local skin temperatures in the control of hand and foot blood flows. European Journal of Applied Physiology, 114, 1679–1689.
Caldwell, J. N., Matsuda-Nakamura, M., & Taylor, N. A. (2016). Interactions of mean body and local skin temperatures in the modulation of human forearm and calf blood flows: A three-dimensional description. European Journal of Applied Physiology, 116, 343–352.
Cannon, P., & Keatinge, W. R. (1960). The metabolic rate and heat loss of fat and thin men in heat balance in cold and warm water. The Journal of Physiology, 154, 329–344.
Casa, D. J., Armstrong, L. E., Kenny, G. P., O’Connor, F. G., & Huggins, R. A. (2012). Exertional heat stroke: New concepts regarding cause and care. Current Sports Medicine Reports, 11, 115–123.
Castellani, J. W., Stulz, D. A., Degroot, D. W., Blanchard, L. A., Cadarette, B. S., Nindl, B. C., & Montain, S. J. (2003). Eighty-four hours of sustained operations alter thermoregulation during cold exposure. Medicine and Science in Sports and Exercise, 35, 175–181.
Castellani, J. W., Young, A. J., Degroot, D. W., Stulz, D. A., Cadarette, B. S., Rhind, S. G., Zamecnik, J., Shek, P. N., & Sawka, M. N. (2001). Thermoregulation during cold exposure after several days of exhaustive exercise. Journal of Applied Physiology, 90, 939–946.
Castellani, J. W., Young, A. J., Ducharme, M. B., Giesbrecht, G. G., Glickman, E., & Sallis, R. E. (2006). American College of Sports Medicine position stand: Prevention of cold injuries during exercise. Medicine and Science in Sports and Exercise, 38, 2012–2029.
Castellani, J. W., Young, A. J., Kain, J. E., Rouse, A., & Sawka, M. N. (1999). Thermoregulation during cold exposure: Effects of prior exercise. Journal of Applied Physiology, 87, 247–252.
Cernych, M., Satas, A., Rapalis, A., Marozas, V., Malciene, L., Lukosevicius, A., Daniuseviciute, L., & Brazaitis, M. (2021). Exposure to total 36-hr sleep deprivation reduces physiological and psychological thermal strain to whole-body uncompensable passive heat stress in young adult men. Journal of Sleep Research, 30, e13055.
Cherubini, J. M., Cheng, J. L., Williams, J. S., & MacDonald, M. J. (2021). Sleep deprivation and endothelial function: Reconciling seminal evidence with recent perspectives. American Journal of Physiology. Heart and Circulatory Physiology, 320, H29–H35.
Costa, R. J., Smith, A. H., Oliver, S. J., Walters, R., Maassen, N., Bilzon, J. L., & Walsh, N. P. (2010). The effects of two nights of sleep deprivation with or without energy restriction on immune indices at rest and in response to cold exposure. European Journal of Applied Physiology, 109, 417–428.
Cramer, M. N., Bain, A. R., & Jay, O. (2012). Local sweating on the forehead, but not forearm, is influenced by aerobic fitness independently of heat balance requirements during exercise. Experimental Physiology, 97, 572–582.
DeWmess, G., Bothorel, B., Hoeft, A., & Candas, V. (1993). Regulation of local sweating in sleep-deprived exercising humans. European Journal of Applied Physiology and Occupational Physiology, 66, 542–546.
Esmat, T. A., Clark, K. E., Muller, M. D., Juvancic-Heltzel, J. A., & Glickman, E. L. (2012). Fifty-three hours of total sleep deprivation has no effect on rewarming from cold air exposure. Wilderness and Environmental Medicine, 23, 349–355.
Fiorica, V., Higgins, E. A., Lampi, P. F., Lategola, M. T., & Davis, A. W. (1968). Physiological responses of men during sleep deprivation. Journal of Applied Physiology, 24, 167–176.
Frank, M. G., & Benington, J. H. (2006). The role of sleep in memory consolidation and brain plasticity: Dream or reality? Neuroscientist, 12, 477–488.
Fujita, M., Lee, D., Ismail, M. S., & Tochihara, Y. (2003). Seasonal effects of sleep deprivation on thermoregulatory responses in a hot environment. Journal of Physiological Anthropology and Applied Human Science, 22, 273–278.
Fullagar, H. H., Skorski, S., Duffield, R., Hammes, D., Coutts, A. J., & Meyer, T. (2015). Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. Sports Medicine, 45, 161–186.
Gage, A. P., Stolwijk, J. A., & Hardy, J. D. (1967). Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environmental Research, 1, 1–20.
Gale, E. A., Bennett, T., Green, J. H., & MacDonald, I. A. (1981). Hypoglycaemia, hypothermia and shivering in man. Clinical Science, 61, 463–469.
Grandou, C., Wallace, L., Fullagar, H. H. K., Duffield, R., & Burley, S. (2019). The effects of sleep loss on military physical performance. Sports Medicine, 49, 1159–1172.
Hardy, J. D. (1971). Thermal comfort and health. ASHRAE Journal, 13, 43–51.
Hom, L. L., Lee, E. C., Apicella, J. M., Wallace, S. D., Emmanuel, H., Klau, J. F., Poh, P. Y., Marzano, S., Armstrong, L. E., Casa, D. J., & Maresh, C. M. (2012). Eleven days of moderate exercise and heat exposure induces acclimation without significant HSP70 and apoptosis responses of lymphocytes in college-aged males. Cell Stress and Chaperones, 17, 29–39.
Kenny, G. P., & Journeay, W. S. (2010). Human thermoregulation: Separating thermal and nonthermal effects on heat loss. Frontiers in Bioscience, 15, 259–290.
Keramidas, M. E., Kolegaid, R., Mekjavic, I. B., & Eiken, O. (2019). Interactions of mild hypothermia and hypoxia on finger vasoreactivity to local cold stress. American Journal of Physiology. Regulatory, Integrative and Comparative Physiology, 317, R418–R431.
Killgore, W. D. (2010). Effects of sleep deprivation on cognition. Progress in Brain Research, 185, 105–129.
Kolka, M. A., Martin, B. J., & Elizondo, R. S. (1984). Exercise in a cold environment after sleep deprivation. European Journal of Applied Physiology and Occupational Physiology, 53, 282–285.
Kolka, M. A., & Stephenson, L. A. (1988). Exercise thermoregulation after prolonged wakefulness. Journal of Applied Physiology, 64, 1575–1579.
Krachki, K., & Deboer, T. (2010). The interrelationship between sleep regulation and thermoregulation. Frontiers in Bioscience, 15, 604–625.
Krachki, K., & Wirz-Justice, A. (1994). Circadian rhythm of heat production, heat rate, and skin and core temperature under unmasking conditions in men. The American Journal of Physiology, 267, R819–R829.
Kundermann, B., Sperrn, J., Huber, M. T., Krieg, J.-C., & Lautenbacher, S. (2004). Sleep deprivation affects thermal pain thresholds but not somatosensory thresholds in healthy volunteers. Psychosomatic Medicine, 66, 932–937.
Landis, C. A., Savage, M. V., Lentz, M. J., & Brengelmann, G. L. (1998). Sleep deprivation alters body temperature dynamics to mild cooling and heating not sweating threshold in women. Sleep, 21, 101–108.
Lowe, C. J., Safati, A., & Hall, P. A. (2017). The neurocognitive consequences of sleep restriction: A meta-analytic review. Neuroscience and Biobehavioral Reviews, 80, 586–604.

Macdonald, I. A., Bennett, T., & Sainsbury, R. (1984). The effect of a 48 h fast on the thermoregulatory responses to graded cooling in man. Clinical Science, 67, 445–452.

Machado-Moreira, C. A., & Taylor, N. A. (2017). Thermogenic and psychogenic recruitment of human eccrine sweat glands: Variations between glabrous and non-glabrous skin surfaces. Journal of Thermal Biology, 65, 145–152.

Mekjavic, I. B., & Elken, O. (2006). Contribution of thermal and nonthermal factors to the regulation of body temperature in humans. Journal of Applied Physiology, 100, 2065–2072.

Moore, J. P., Walsh, N. P., & Zurawlew, M. J. (2015). Daytime napping results in an underestimation of thermal strain during exercise in the heat. Occupational and Environmental Medicine, 72, 753.

Muginstein-Simkovitch, E., Dagan, Y., Cohen-Zion, M., Waissegren, B., Ketko, I., & Heled, Y. (2015). Heat tolerance after total and partial acute sleep deprivation. Chronobiology International, 32, 717–724.

Oliver, S. J., Harper Smith, A. D., Costa, R. J., Maassen, N., Bilzon, J. L., & Walsh, N. P. (2015). Two nights of sleep deprivation with or without energy restriction does not impair the thermal response to cold. European Journal of Applied Physiology, 115, 2059–2068.

Passias, T. C., Meneilly, G. S., & Mekjavic, I. B. (1996). Effect of hypoglycemia on thermoregulatory responses. Journal of Applied Physiology, 80, 1021–1032.

Pugh, L. G. (1966). Accidental hypothermia in walkers, climbers, and campers: Report to the Medical Commission on Accident Prevention. British Medical Journal, 1, 123–129.

Rav-Acha, M., Hadad, E., Epstein, Y., Heled, Y., & Moran, D. S. (2004). Fatal exertional heat stroke: A case series. The American Journal of the Medical Sciences, 328, 84–87.

Ravanelli, N., & Jay, O. (2020). The change in core temperature and sweating response during exercise are unaffected by time of day within the wake period. Medicine in Science in Sports and Exercise. https://doi.org/10.1249/MSS.0000000000002575. Online ahead of print.

Refinetti, R., & Menaker, M. (1992). The circadian rhythm of body temperature. Physiology and Behaviour, 51, 613–637.

Reif, R., Willmott, A., Mee, J., Gibson, O., Saunders, A., Hayes, M., & Maxwell, N. (2018). 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 Science, 36, 348–355.

Rintamaki, H. (2000). Predisposing factors and prevention of frostbite. International Journal of Circumpolar Health, 59, 114–121.

Salín-Pascual, R. J., Ortega-Soto, H., Huerto-Delgadillo, L., Camacho-Arroyo, I., Roldán-Roldán, G., & Tamarkin, L. (1988). The effect of total sleep deprivation on plasma melatonin and cortisol in healthy human volunteers. Sleep, 11, 362–369.

Satinoff, E. (1996). Behavioral thermoregulation in the cold. In M. J. Fregley & C. M. Blatteis (Eds.), Handbook of physiology, Section 4, Environmental physiology (pp. 481–505). Oxford University Press.

Savourey, G., Arnal, P. J., Tardo-Dino, P. E., Drogou, C., Van Beers, P., Bougard, C., Rabat, A., Dispersyn, G., Malgoyre, A., Leger, D., Gomez-Merino, D., & Chennaoui, M. (2017). Protective effects of exercise training on endothelial dysfunction induced by total sleep deprivation in healthy subjects. International Journal of Cardiology, 232, 76–85.

Sauvet, F., Bourrillhon, C., Besnard, Y., Alonso, A., Cottet-Emard, J. M., Savourey, G., & Launay, J. C. (2012). Effects of 29-h total sleep deprivation on local cold tolerance in humans. European Journal of Applied Physiology, 112, 3239–3250.

Sauvet, F., Leftheriotis, G., Gomez-Merino, D., Langrume, C., Drogou, C., Van Beers, P., Bourrillhon, C., Florence, G., & Chennaoui, M. (2010). Effect of acute sleep deprivation on vascular function in healthy subjects. Journal of Applied Physiology, 108, 68–75.

Savourey, G., & Bittel, J. (1994). Cold thermoregulatory changes induced by sleep deprivation in men. European Journal of Applied Physiology and Occupational Physiology, 69, 216–220.

Sawka, M. N., Gonzalez, R. R., & Pandolf, K. B. (1984). Effects of sleep deprivation on thermoregulation during exercise. The American Journal of Physiology, 246, R72–R77.

Schlader, Z. J., Sackett, J. R., Sarker, S., & Johnson, B. D. (2018). Orderly recruitment of thermoeffectors in resting humans. American Journal of Physiology. Regulatory, Integrative and Comparative Physiology, 314, R171–R180.

Schlader, Z. J., & Vargas, N. T. (2019). Regulation of body temperature by autonomic and behavioral thermoeffectors. Exercise and Sport Sciences Reviews, 47, 116–126.

Taylor, N. A. S., & Gordon, C. J. (2019). The origin, significance and plasticity of the thermoafferent thresholds: Extrapolation between humans and laboratory rodents. Journal of Thermal Biology, 85, 102397.

Tokizawa, K., Sawada, S., Tai, T., Lu, J., Oka, T., Yasuda, A., & Takahashi, M. (2015). Effects of partial sleep restriction and subsequent daytime napping on prolonged exertional heat strain. Occupational and Environmental Medicine, 72, 521–528.

Wilson, O., & Goldman, R. F. (1970). Role of air temperature and wind in the time necessary for a finger to freeze. Journal of Applied Physiology, 29, 658–664.

Young, A. J., Castellani, J. W., O’Brien, C., Shippee, R. L., Tikuisis, P., Meyer, L. G., Blanchard, L. A., Kain, J. E., Cadarette, B. S., & Sawka, M. N. (1998). Exertional fatigue, sleep loss, and negative energy balance increase susceptibility to hypothermia. Journal of Applied Physiology, 85, 1210–1217.

Zeitzer, J. M., Duffy, J. F., Lockley, S. W., Dijk, D. J., & Czeisler, C. A. (2007). Plasma melatonin rhythms in young and older humans during sleep, sleep deprivation, and wake. Sleep, 30, 1437–1443.

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