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Sleep environments and sleep physiology: A review

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ABSTRACT

Sleep loss impairs task performance and post-physical activity recovery, cognitive performance and mood, heightens fatigue and decreases vigour; poor sleep quality impairs decision-making, the speed and accuracy of task performance, and post-exercise recovery.

Sleep time and quality are affected by age, psychological and physiological conditions, culture and environmental factors. Skin temperature, rapid temperature change and sweating during sleep can significantly reduce sleep quality. Hence, the thermal properties of bedding and sleepwear, both in steady-state and transient ambient temperature conditions, are logically important factors.

Research to date on sleeping thermal microclimates and their effect on sleep quality is scarce. This present review covers the fundamental elements of human sleep, highlighting physically active people, such as athletes, and the influence of sleepwear and bedding on sleep thermal microclimates, as well as the research methods that have been and could be used in this field. This review identifies opportunity for future research direction and approaches to understanding thermal environments that may support better human sleep.

1. Introduction

Sleep is essential for emotional, physical and cognitive wellbeing (Hirshkowitz et al., 2015) and occupies around one third of a person's life (Lee, 1997). Sleep enables the human body to recover after activity, ensuring optimal subsequent functioning (Vyazovskiy and Delogu, 2014). Sleep deprivation and loss are closely associated with cognitive impairment, mood changes and hormonal abnormalities (Dinges et al., 1997; Ferrara and De Gennaro, 2001; Carskadon and Dement, 2005).

Sleep complaints are common: a meta-analysis of sleep quality research concluded that 15–35% of adults have regular sleep disruptions, such as sleep onset latency (SOL), insufficient sleep duration or frequent waking during the night (Mollayeva et al., 2016). Researchers have identified numerous causes of sleep deprivation and insomnia (American Academy of Sleep Medicine, 2005). Circadian rhythm abnormalities are known to influence core body temperatures, reducing sleep quality (Lack et al., 2008), as do environmental influences such as high ambient temperatures and humidity, noise, and shift work (Lack et al., 2008; Okamoto-Mizuno et al., 1999), psychological factors such as anxiety, and physiological factors such as pain, fatigue and recovery needs (Bonnet and Arand, 1996; Nadler et al., 2003; Lack et al., 2008).

Some research has suggested that skill development and learning is enhanced during memory consolidation when asleep (rapid eye movement (REM) stages), and therefore optimal sleep supports skill execution and hence task performance (Walker and Stickgold, 2005). In addition, the sleep episode following initial skill practice is considered to be important for consolidation of new skill development (Walker and Stickgold, 2005).

Acute and cumulative sleep losses reduce the overall restorative quality of human sleep and consequently health and wellbeing (Ferrara and De Gennaro, 2001; Samuels, 2009). A strong body of evidence shows that sleep contributes significantly to molecular and cellular restoration and maintenance, brain growth, immune system balance, and recovery from illness and injury (Moldofsky et al., 1989; Walters, 2002; Nadler et al., 2003; Samuels, 2009; Abel et al., 2013; Vyazovskiy and Harris, 2013; Copenhaver and Diamond, 2017). For example, for athletes, training for competitive performance and prolonged and/or high intensity physical activity requires sufficient pre-event sleep and post-event recovery to support performance (Dale, 2004; Davenne, 2009). Further, optimal athletic performance requires the alternation of training loads with recovery to avoid build-up of fatigue and overtraining (Smith, 2003), which can result in performance depletion and injuries (Smith, 2003; Dale, 2004; Copenhaver and Diamond, 2017). However, research shows that athletes get less sleep than non-athletes

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Abbreviations: NREM, non-rapid eye movement; PSG, polysomnography; PSQI, Pittsburgh Sleep Quality Index; REM, rapid eye movement; SD, sleep deprivation; SE, sleep efficiency; SOL, sleep onset latency; SR, sleep restriction; SWS, slow wave sleep; TST, total sleep time

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and frequently less sleep than recommended (Walters, 2002; Halson, 2008; Venter, 2012), despite quality sleep being critical for intensive physical performance. This highlights the need for better understanding of how improved sleeping environments can positively influence the quality of human sleep.

To date, few researchers have focused on the contribution of comfort to sleep quality (Lan et al., 2017), particularly conditions within the sleep microclimate. Ambient conditions, such as air temperature, humidity and air flow, are known to affect sleep comfort and quality (Okamoto-Mizuno and Mizuno, 2012; Lan et al., 2014, 2017); however, the entire sleep system, which includes the bedding ensemble and sleepwear, should be considered holistically along with the ambient conditions. For example, a naked sleeper has a microclimate between the skin and the cover/s, but introduction of sleepwear creates a more complex system with addition of a next-to-skin (between the skin and the sleepwear) microclimate that interacts with the microclimate between the sleepwear and the cover/s.

Little is known about the effect of the sleeping system on the sleep microclimate, and therefore of their combined effect on sleep quality. This review explores current knowledge of sleep and its role in thermal biology, human recovery and task performance, with particular focus on the sleeping thermal microclimates created by bedding and sleepwear. Its aim is to create a foundation for future research aimed at improving understanding of the effects of bedding and sleepwear on thermal biology in relation to intensively physically active people and to the broader population.

2. Methodology

A systematic review approach was utilised to provide a comprehensive overview of existing research evidence about the interactions between human sleep, sport, and sleepwear and bedding textiles.

Relevant studies were located using Scopus, Web of Science, Google Scholar and EBSCOhost (which includes Textile Technology Complete and SportDiscus databases) between July and September 2017. The search strategy involved the primary keyword “sleep” combined with “athlete”, “athletic”, “sport”, “textile”, and/or “fabric”. Only papers written in English were included; publication date was not restricted. Publications were also sourced manually from the bibliographies of original manuscripts.

The authors initially assessed the retrieved records based on the relevance of their titles and abstracts to the following topics:

- human sleep physiology;
- sleep of athletes;
- sleep and human/athletic performance;
- sleep and human/athletic recovery;
- sleeping ambient and thermal environments; and
- methods used in sleep research.

The full texts of publications deemed to have a title and abstract relevant to one or more of the topics above were examined to determine their suitability. Ultimately, 139 publications were included in the review.

3. Sleep and intensive physical performance and recovery

The relationships between intensive physical and athletic performance, recovery and sleep have received significant attention in sleep research. It is well accepted that good-quality sleep is vital to optimal physical performance (Halson, 2008; Fullagar et al., 2015b). For example, it is known that athletes require more sleep than sedentary people (Davenne, 2009), and 9–10 h of predominantly nocturnal sleep is ideal (Bompa and Haff, 2009; Halson, 2014), whilst (as noted earlier) 7–9 h is recommended for other healthy adults (Ferrara and De Gennaro, 2001; Hirshkowitz et al., 2015). However, few athletes achieve this optimal amount of sleep, and athletes commonly suffer from poor sleep quality (Samuels, 2009), with factors such as intensity and duration of training schedules, pre-competition nervousness and anxiety, jetlag and travel, and unusual or new environments identified as key causes (Davenne, 2009; Sargent et al., 2014b; Juliff et al., 2015). In another study, Leeder et al. (2012) compared the sleep of Olympic athletes with an age- and sex-matched non-athletic population using wristwatch autography. The results suggested that while the athletes had a similar mean length of sleep they experienced poorer sleep quality than the non-athletic control group.

Table 1
Overview of effects of sleep disruption on performance in sporting activities (source: (Halson, 2008), adapted from (Reilly and Edwards, 2007)).

Characteristics	Sports	Effects
Low aerobic	Road cycling, aiming sports	Increased errors
Moderate aerobic, high concentration	Team sports	Decreased decision-making
High aerobic	Running 3000 m, swimming 400 m	Marginal
Aerobic/anaerobic	Swimming, middle distance running	Decreased power
Anaerobic	Sprints, power events	Marginal
Repeat anaerobic	Jumping events, weight training	Increased fatigue

Studies of athletes and their sleep quality have produced divergent conclusions. Numerous studies have shown that athletes sleep less than the recommended amount per day, and report lower sleep quality with more sleep disruptions than non-athletes (Walters, 2002; Erlacher et al., 2011; Leeder et al., 2012; Venter, 2012; Sargent et al., 2014a; Fullagar et al., 2015a; Juliff et al., 2015; Staunton et al., 2017). However, other studies show that sleep quality benefits are associated with exercise and physical activity (Youngstedt et al., 1997; Driver and Taylor, 2000; Brand et al., 2010; Kredlow et al., 2015).

Table 1 provides an overview of the effects of sleep disruption on performance in a range of sporting activities. It suggests that the effects on performance are varied, from physical impacts (reduced power and increased fatigue) to cognitive impairment (more errors and impaired decision-making).

Sleep's restorative and maintenance effects include positive impacts on the immune and endocrine systems and maintenance of cognitive function, and consequently it strongly affects not only athletic performance but recovery (Spiegel et al., 1999; Frank, 2006; Halson, 2008; Davenne, 2009; Samuels, 2009). Optimising recovery from training and competition is critical (Kellmann, 2010); appropriate strategies are needed for elite athletes to recover from heavy training schedules and competitive events to ensure optimal future performance (Kellmann, 2010; Halson, 2013a). Whilst the entire sleep process supports the process of recovery or recuperation, the greatest benefits occur during stages 3 and 4 (Venter, 2012), when metabolic activity is at its lowest (Walters, 2002). Melatonin and growth hormones released during sleep are thought to stimulate and enhance the immune system, supporting tissue growth and injury recovery (Moldofsky et al., 1989). Along with exercise, sleep is regarded as one of the most important non-pharmacological initiators of the secretion of growth hormone (Godfrey et al., 2003), which plays a major role in tissue regeneration and repair (Copenhaver and Diamond, 2017). Further, over 90% of these hormones are secreted during non-REM (NREM) stages of sleep, commencing at the onset of sleep and escalating in the first slow-wave sleep (SWS) phase (Gunning, 2001). If metabolic rate increases during the day, such as during training or competition, growth hormone levels rise during the following night (Shapiro, 1981). It is also understood that the length of SWS phases and the level of growth hormone secretion are positively correlated (Van Cauter et al., 1997); however, if the sleep cycles of the athlete are disrupted or diminished, particularly with loss of SWS, levels fall significantly (Davenne, 2009). It is suggested that athletes should sleep (nap) during the day to stimulate growth hormone release (Venter, 2012).

NREM sleep is linked to lower oxygen consumption, protein construction and movement of fatty acids, which are proposed to increase restorative processes and assist injury recovery (Fullagar et al., 2015a; Copenhaver and Diamond, 2017). Further, it has been shown that sleep loss can slow glucose metabolism by up to 40% (Spiegel et al., 1999), depleting this key athletic energy source.

In summary, while there is sufficient evidence that improved sleep supports optimal athletic performance, we found no studies of elite athletes that assessed sleeping systems and sleep microclimates across various scenarios that could influence their sleep quality and hence athletic performance and recovery.

4. Sleep physiology

To understand the importance and possible effects of sleeping thermal environments and bedding systems on human sleep, it is necessary to outline sleep physiology.

Sleep involves complex physiological and behavioural processes that have been studied extensively but are not fully understood (Carskadon and Dement, 2005; Deboer, 2013). Two processes are commonly thought to be significant in sleep physiology: homeostasis and the circadian rhythm (Czeisler et al., 1980; Borbély, 1982; Dement, 2005).

Homeostatic processes maintain the internal stability of the body. They regulate the inclination for sleep (Fisher et al., 2013): increasing the urge to sleep with prolonged wakefulness, reducing it as sleep time extends, and rising again with wakefulness (Fig. 1a) (Fisher et al., 2013). When a person is deprived of sleep, the loss is compensated by increasing the propensity for sleep and/or deepening of sleep in the next sleep cycle (Dement, 2005).

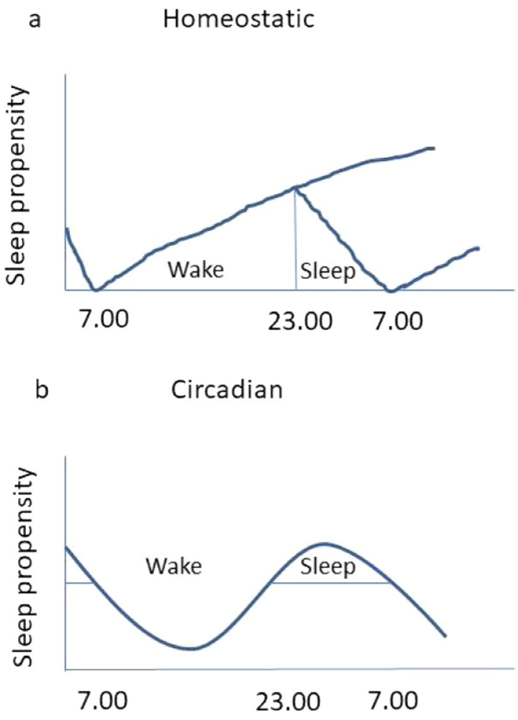


Fig. 1. Sleep propensity (%) and (a) homeostatic drive and (b) circadian drive during 24-h Time course (X axis): adapted from Fisher et al. (2013). "The homeostatic drive for sleep increases sleep propensity with prolonged wakefulness. Sleep pressure declines following sleep, but increases again at waking. The circadian regulation of sleep creates a drive for wakefulness during the day, which declines at night. As such, sleep propensity is low during the day, but increases at night" (Fisher et al., 2013, p.158).

Sleep is also regulated by our circadian rhythms, which are a 24-h internal day-night clock cycle consisting of patterns of wakefulness and sleepiness (Fig. 1b) (Davenne, 2009; Fisher et al., 2013). Human sleep studies that eliminated participants' cues related to time concluded that the timing and length of sleep are directly related to circadian phases (Czeisler et al., 1980; Zulley et al., 1981).

A National Sleep Foundation (USA) systematic review (Hirshkowitz et al., 2015) found that the amount of sleep humans need is strongly related to age. For example, the amount of sleep needed for optimal health in young adults and adult humans is 7–9 h per night, reducing as we get older (Hirshkowitz et al., 2015).

It is also important to define what is meant by sleep quality and the measures used to characterise poor or good quality sleep. Polysomnography (PSG) is an objective method widely used to measure determinants of sleep quality such as total sleep time (TST), SOL, sleep efficiency (SE), and duration of sleep stages (i.e. stages 1–4 and REM sleep) (Krystal and Edinger, 2008). The most widely used subjective method for evaluation of sleep quality is the Pittsburgh Sleep Quality Index (PSQI) (Mollayeva et al., 2016), a self-report questionnaire that rates various aspects of sleep: subjective sleep quality, SOL, TST, SE, sleep disturbances, use of sleeping medication, and daytime dysfunction (Buysse et al., 1989). Common measures of poor sleep quality include SOL $>$ 30 min; wakefulness after sleep onset of $>$ 30 min; TST of $<$ 6.5 h per night; and SE of $<$ 85%. In addition, daytime impairment, such as sleepiness, fatigue, low energy and enthusiasm, and poor attention are seen as indicators of poor sleep characteristics (Shelgikar and Chervin, 2013; Mollayeva et al., 2016).

4.1. *Sleep stages*

Human sleep has two states: NREM and REM sleep (Fisher et al., 2013; Vyazovskiy and Delogu, 2014). During nocturnal sleep, brain activity cycles between distinct slow activity (NREM) and highly active (REM) episodes (Saper et al., 2010). The length of each cycle will change across a full night's sleep, with REM phases becoming longer (Carskadon and Dement, 2005).

NREM sleep is divided into four stages (Leung and Ge, 2013), with each stage representing progressively deeper sleep (Carskadon and Dement, 2005). Stage 1 covers the onset of sleep and is characterised as light sleep; stage 2 is the stage in which muscles start to shut down. Stages 3 and 4 are also known as SWS, which is deep sleep with prominent slow brain waves, and is associated with minimal mental activity (Saper et al., 2010). NREM sleep typically accounts for 75–80% of TST; NREM stages of sleep are considered to be restorative and recuperative periods for the body (Gunning, 2001).

The REM state of sleep, which is associated with dreaming, accounts for around 20–25% of total sleep time (Carskadon and Dement, 2005). During this stage, the eyes move rapidly in bursts and muscle atonia occurs (Carskadon and Dement, 2005). Brain activity throughout REM stages is considered to be similar to that when awake (Vyazovskiy and Delogu, 2014), with REM described as a "highly activated brain in a paralysed body" (Carskadon and Dement, 2005, p. 14).

There are many competing theories about the biological function of REM sleep (Roffwarg et al., 1966; Vertes and Eastman, 2000; Siegel, 2011; Vyazovskiy and Delogu, 2014). However, it is undoubtedly a vital process, facilitating important learning and memory processes and aiding in overcoming stress (Siegel, 2011; Horne, 2013).

Fig. 2 shows an average sleep pattern in a normal 19-year-old adult across a single night of sleep (Carskadon and Dement, 2005). It depicts each sleep stage and the body movement activity experienced in REM stages of sleep.

It is proposed that both neural network recovery and network selection and restoration for optimal functioning in post-sleep waking periods are only fully enabled with optimal cyclic phasing between NREM and REM stages of sleep (Vyazovskiy and Delogu, 2014). It is

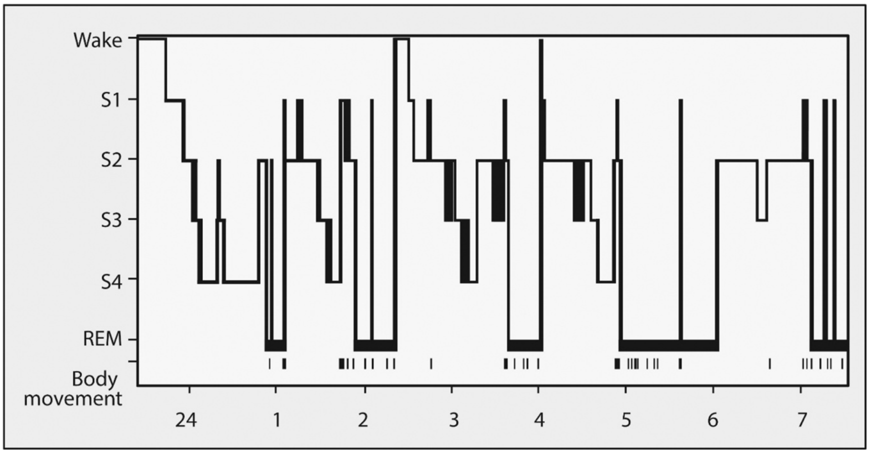


Fig. 2. Example of nocturnal sleep stages S1-S4 (reproduced from Carskadon and Dement, 2005). "The progression of sleep stages across a single night in a normal young adult volunteer is illustrated in this sleep histogram. This histogram was drawn on the basis of a continuous overnight recording of electroencephalogram, electrooculogram, and electromyogram in a normal 19-year-old man. The record was assessed in 30-second epochs for the various sleep stages. REM, rapid eye movement" (Carskadon and Dement, 2005, p.18). Y axis- sleep stages, X axis - 24-h Time course and hours of sleep, secondary histogram reflects body movement during sleep.

clear that both ambient and bedding environments have to be considered in relation to the cyclic nature of sleep and possibility of varying and complex demands placed on these thermal environments for the facilitation of high-quality sleep.

4.2. *Thermoregulation and sleep*

Thermoregulation is an important component of the cyclic nature of human sleep. Thermoregulation refers to the physiological processes the human body employs to maintain core body temperature close to 37 °C (i.e. ± °C) (Parsons, 2014). Thermal homeostasis is dependent on the balance between heat production and heat loss, which is influenced by both environmental and behavioural factors. If heat gains are greater than heat losses the core body temperature increases, and vice versa (Parsons, 2014). The body self-regulates by altering skin blood flow, hormone levels and sweating to stay within the optimal thermal range and to maintain its homeostasis.

Body thermoregulation is active through sleep stages 1–4, but is greatly reduced during REM sleep (Bach et al., 2002; Amici et al., 2005); functions such as sweating and shivering in response to changes in the thermal environment cease (Parmeggiani, 1980; Carskadon and Dement, 2005) or are reduced relative to the other stages of sleep (Henane et al., 1977; Haskell et al., 1981a; Muzet et al., 1983; Bach et al., 2002). Therefore, extremes of temperature and humidity in the sleep environment can affect sleep quality, implying that maintaining an optimal thermal sleeping environment will support high-quality sleep.

Table 2 summarises key sleep studies covered in this review.

4.3. *Body temperature and sleep*

As mentioned earlier, sleep is regulated by circadian rhythms and homeostatic processes (Borbély, 1982; Gilbert et al., 2004; Fisher et al., 2013). However, thermoregulatory processes can also influence sleep readiness (Gilbert et al., 2004). Nocturnal sleepiness and sleep onset (NREM stage 1) are closely associated with core temperature decrease (Barrett et al., 1993; Murphy and Campbell, 1997) and increase in peripheral skin temperature (Kräuchi, 2007) as part of preparation for nocturnal sleep (Van den Heuvel et al., 1998). While a person is awake, the proximal (i.e. torso) skin temperature can exceed the distal (i.e. extremities) skin temperature by as much as 2.5 °C (Kräuchi et al., 1999). As sleepiness increases the core body temperature drops but the distal skin temperature rises until they are approximately equal, around the time of sleep onset (see Fig. 3). Van den Heuvel et al.'s (1998) study of 14 male subjects confirmed that a significant rise in distal skin temperature and related decline in core temperature heralds the onset of sleep.

These changes in temperature correlate with increased melatonin production, which in turn induces vasodilation in the fingers and toes and increases the blood flow to the distal skin, increasing its temperature (Gilbert et al., 2004; Kräuchi, 2007; Kräuchi and Deboer, 2011). A correlation between salivary melatonin content and the distal skin temperature can be seen in Fig. 3. This suggests that the changes in temperature can be interpreted as a redistribution of body heat from the core to the distal skin, which is due to the effect of melatonin (Kräuchi, 2007; Kräuchi and Deboer, 2011).

According to Kräuchi (2007) and Kräuchi and Deboer (2011), simply a change from the upright to the supine position – that is, lying down – increases both the proximal and the distal skin temperatures. This explains the jump in both proximal and distal skin temperatures in the very early stages of sleep (Fig. 3). This initial skin temperature increase lasts 1–2 h. Therefore, it is reasonable to accept that the adequate next to skin microclimate temperature is important for sleep onset.

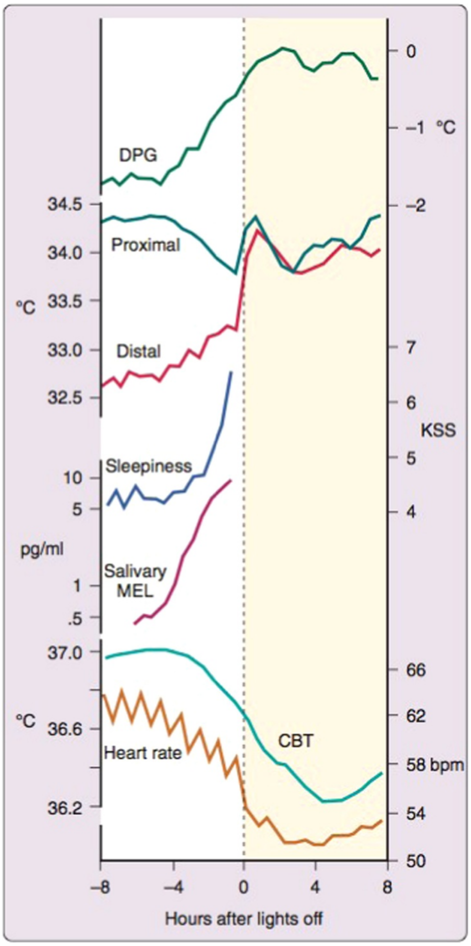
Core body temperature is defined as the temperature around deep body structures such as the internal organs, and is often measured as the rectal temperature or the oesophageal temperature (Lefrant et al., 2003). During waking hours, core body temperature is usually around 37 °C; however, for several hours prior to nocturnal sleep onset, it drops gradually in preparation for sleep (Murphy and Campbell, 1997; Gilbert et al., 2004) (Fig. 3), and continues to drop once asleep (Kräuchi and Deboer, 2011), reinforcing sleep duration. The drop in core body temperature correlates with the circadian cycles and prompts sleepiness (Gilbert et al., 2004) and melatonin production, which signals the body to prepare for sleep. Core temperature decrease in readiness for sleep is principally achieved through a rise in skin blood flow and peripheral heat loss, which culminates in higher peripheral skin temperature (Rogers et al., 2007). We elaborate upon this important physiological process in the following section.

Researchers have found that skin temperature also changes across different phases of sleep, increasing during REM sleep, with the scale of this effect appearing to be dependent upon the specific environmental conditions. In a study involving three male subjects wearing only swimming trunks and without any covers (Henane et al., 1977), researchers found that across the night the skin temperature decreased significantly in neutral conditions (30–34 °C), whereas in warm conditions (35–39.5 °C) it slightly increased across the night. However, in these warm conditions, skin temperature increased by between 0.5 °C and 2 °C during REM sleep. Authors proposed that the variation in skin temperature was due to the influence of circadian rhythms (i.e., long-lasting changes) and that short-duration changes were induced only during REM phases of sleep.

Henane et al. (1977) monitored subjects one night per week over one year, in an environmental chamber with a relative humidity of 45% and an air velocity of 0.15 m/s. A representative example of their results (for one of their subjects) is shown in Fig. 4 – continuous

Table 2
Summary of key sleep studies.

	Study	Number of participants, male (M) or female (F)	Ambient conditions			Core temperature (T Rectal)	Skin temperature °C (T Skin)	Sleep quality	Bedding	Sleepwear
			Temperature (T),°C	Relative humidity (RH), %	Air velocity (AV), m/s					
1	Candas et al. (1982)	5 M	17–41 transient	Not reported	0.2	Not reported	External heat stimulations resulted in higher skin temperature during REM and SWS than if no heat stimulation occurred.	Heat stimulations during sleep interrupted SWS 30% of times; REM 67% of times.	No covers	Briefs only
2	Haskell et al. (1981)	6 M	21, 24, 29, 34 and 37	20–60	Not reported	T Rectal showed significant decreases in all temperatures, except 37 C	T Skin remained relatively stable at 29 °C and 34 °C, after sleep onset; gradual rise in T Skin at 37 °C after 2 h of sleep	Linear drop in length of SWS and REM as ambient temperature rose above 29 °C (thermoneutral)	No covers	Briefs only
3	Henane et al. (1977)	3 M	30–34- neutral	45	0.15	T Rectal dropped in line with circadian rhythm	T Skin dropped significantly across the night	Sleep patterns followed circadian rhythms	No covers	Swimming trunks
			35–39.5- warm	45	0.15	T Rectal remained steady	T Skin increased slightly across the night, but rose by 0.5 °C– 2 °C during REM	REM sleep induced rise in T Skin		
4	Karacan et al. (1978)	10 M	22 Baseline (BL); 39 High blanket temperature (HBT)	Not reported	Not reported	T Rectal remained constant at 37 °C (HBT); Reduced from 36° to 34.5°C (BL)		HBT sleep had less TST; longer and more frequent awakening episodes; reduced SWS and REM	Top and bottom blanket (BL); Fluid heated blanket (HBT)	Underwear shorts
5	Lan et al. (2014)	9 M, 9 F	23, 26, 30	50%, 55%, 68%	0.06–0.08	Not reported	T Skin increased with rise in T ambient	Positive correlation between air temperature and skin temperature; SWS was lowest at 30 °C and significantly lower than SWS at 26 °C.	Thin blanket	Short sleeved sleepwear
6	Libert et al. (1991)	8 M	20, 35	50%	0.2	T Oesophageal significantly higher at 35 across the night of sleep compared to 20 °C	T Skin significantly higher at 35 °C across the night of sleep compared to 20 °C	Sleep efficiency and TST decreased at 35 °C compared with 20 °C; Wakefulness and sleep stage 1 significantly higher at 35 °C	Cotton sheet and wool blanket; cotton sheet cover	Pyjamas; Underwear shorts
7	Muzet et al. (1983)	5 M	13, 16, 19 22 and 25	37–80	0.2			The mean REM cycle length reduced significantly as temperature increased from 13 °C to 25 °C	Cotton sheets and wool blanket	pyjamas
8	Okamoto-Mizuno et al. (1999)	7 M	29, 35	50, 75		T Rectal was higher at 35 °C/75% than all other conditions.	Mean T Skin higher at 35 °C/ 50% and 35 °C/75% than at 29 °C/50% and 29 °C/75%.	Wakefulness significantly higher at 35 °C/75%. Lower sleep efficiency index (SEI) and stage 3, 4 and REM at 35 °C/75% than at 29 °C/50% and 35 °C/50%.	Bed sheet	Shorts
9	Okamoto-Mizuno et al. (2004)	8 M	26, 26–32;	50, 50–80	Not re ported	T Rectal increased with rise in T ambient	T skin increased with rise in T ambient	Sleep efficiency decreased at 26–32 °C compared with 26 °C; Wakefulness and sleep stage 1 significantly higher at 26–32 °C	Bed sheet and blanket	Short sleeve top and pants; underwear
			2/ 26, 32–26	50%, 80–50%		T Rectal increased with rise in T ambient	T Skin increased with rise in T ambient	Sleep efficiency decreased at 32–26 °C compared with 26 °C; Wakefulness and sleep stage 1 significantly higher at 32–26 °C		
10	Tsuzuki et al. (2004)	9 M	26, 32	50, 80	Not re ported	T Rectal remained constant at 32 C/80%; Reduced across the night at 26 C/50%	T Skin was significantly higher at 32 C/80%	Wakefulness and sleep stage 1 significantly higher at 32 C/50%; stage 2 and 4, sleep efficiency significantly lower at 32 C/50%	Bed sheet and blanket	Short sleeve top and pants; underwear



CBT = core body temperature; DPG = distal-proximal skin temperature gradient; Distal = distal skin temperature; KSS = the Karolinska sleepiness scale, a subjective rating of sleepiness; MEL = melatonin; Proximal = proximal skin temperature;

bpm, beats/min

Fig. 3. Physiological measurements for eight hours before and eight hours after “lights off” and going to sleep (reproduced from Kräuchi and de Boer, 2011). ”Time course of heart rate core body temperature (CBT), and its rate of change, salivary melatonin, sleepiness, distal and proximal skin temperatures, and the distal-proximal skin temperature gradient (DPG) in a baseline 7.5-h constant routine followed by a 7.5-h sleep period, yellow area. Continuously measured data are plotted in 30-min bins. Mean values of N = 18 male subjects (± SEM). Note: Distal and proximal skin temperatures exhibit inverse time course before lights off, but were nearly indistinguishable about 1 h there- after. Heart rate reflects the study protocol rhythm of one hourly food and water intake before lights off and declined sharply thereafter. Mean sleep onset latency: 12 min ± 4 min” (Kräuchi and de Boer, 2011, p. 325).

recordings of the rectal temperature (Tre) and the mean skin temperature (Tsk), as well as weight loss (primarily due to sweat) during sleep. The horizontal lines represent periods of REM sleep (see also Fig. 3). Fig. 5 clearly shows that skin temperature rises in cycles in line with occurrences of REM stages and declines upon cessation of REM. The nomenclature for Tg is omitted in the original paper, but this almost certainly relates to ambient temperature, which ranged from 32 °C to 39.5 °C.

In another human study conducted in ambient temperatures of 29 °C, 34 °C, and 37 °C, Haskell et al. (1981a) found that the skin temperature increased following sleep onset and remained relatively stable during the night. Skin temperature rose only slightly – by 0.1 °C – for their near-nude subjects during REM sleep. However, in temperatures below thermoneutral conditions (i.e. 21 °C and 24 °C), they detected no rise in the subjects’ skin temperature during REM sleep. In this study, the relative humidity varied from around 20% for the warmer ambient temperatures to around 60% for the colder ambient temperatures, and the influence of air flow around the participants was restricted.

Candas et al. (1982) found that variations in skin temperature in REM phases led to greater sleep disruption than equivalent changes during SWS (a finding confirmed by Carskadon and Dement, 2005).

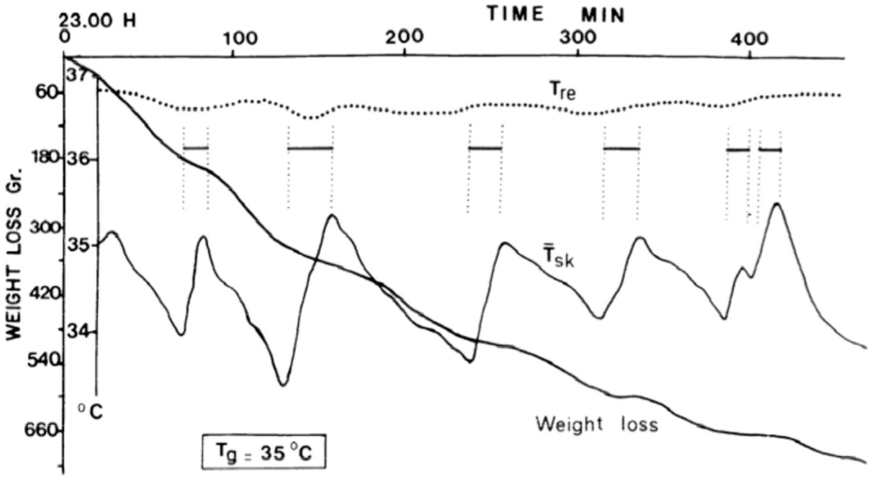


Fig. 4. Rectal temperature (Tre), mean skin temperature (Tsk) and weight loss of sleepers (reproduced from Henane et al., 1977). “Three healthy male subjects, aged 24, 25, and 27 yr participated in the study; experiments were performed on each subject once a week and over a period of 1 yr. Continuous recordings of body temperatures (Tre and Tsk), curve of weight loss during nocturnal sleep of a representative subject. Horizontal bars indicate REM sleep periods” (Henane et al., 1977, p. 50–55). The nomenclature for Tg is omitted in Henane et al. (1977), but this almost certainly relates to ambient temperature, which ranged from 32 °C to 39.5 °C.

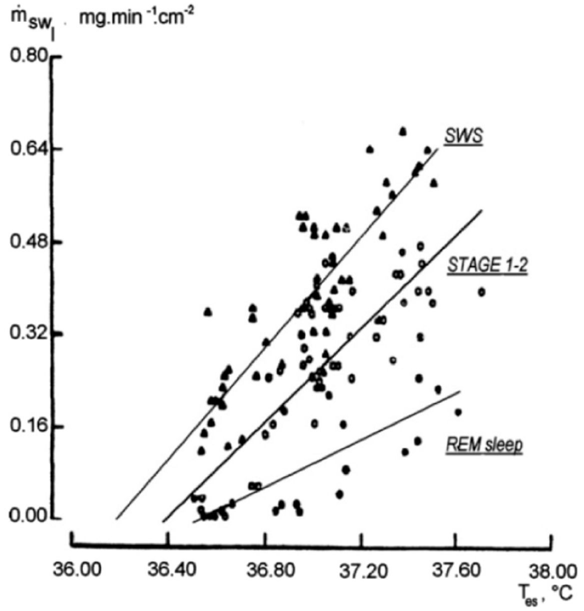


Fig. 5. Relationship between the local sweating rate (msw) and the oesophageal temperature (Tes) during slow wave sleep (SWS, sleep stage 2, and REM sleep in adult humans (reproduced from Libert and Bach, 2005).

Candas et al. (1982) studied nude male subjects, sleeping without covers, in an environmental chamber with ambient temperature rising from 25 °C to 41 °C. It was also found that sleep disruption was more pronounced when the skin was cooling than when heating.

The fact that skin temperature during REM sleep substantially affects sleep quality (if the skin temperature is too high or low, or if the rate of change is too rapid) implies that stable ambient and bedding microclimates support good sleep patterns. According to Leung and Ge (2013), a skin temperature of 35 °C or higher will cause discomfort and reduce the quality of sleep. Skin temperature changing as a result of variable ambient or next-to-skin thermal conditions can affect the length of sleep stages and therefore decrease sleep quality (Candas et al., 1982). Clearly, not only variable ambient conditions affect sleep quality; bedding sleeping systems and the thermal conditions they provide to the sleeper are critical.

Numerous researchers have studied the effect of ambient temperature on sleep quality (Henane et al., 1977; Haskell et al., 1981b), but few (Candas et al., 1982; Muzet et al., 1984; Okamoto-Mizuno et al., 2005) have evaluated the result of continuous variation in the ambient temperature during sleep. Moreover, the literature contains no research on variations in skin temperature during REM sleep with subjects using covers – a surprising and potentially important gap. In addition, we found no research on the relationship between sleeping system, skin microclimates and skin temperature changes. A few researchers have investigated ambient microclimate conditions and their effect on sleep quality (Tsuzuki et al., 2004; Lan et al., 2017), yet it is advocated that aspects affecting thermal comfort, such as skin temperature and next to skin humidity, are largely influenced by the sleep microclimate (Bischof et al., 1993). The influence of skin temperature and its variation on sleep quality implies that the thermal properties of bedding in different ambient conditions are important for achieving quality sleep.

4.4. Sweating during different stages of sleep

As discussed earlier, thermoregulatory processes are suppressed during REM sleep stages as opposed to NREM stages and daily wakefulness stages (Parmeggiani, 1980, 1986). Sweating rates during REM sleep stages are lower than during other stages of sleep (Henane et al., 1977; Haskell et al., 1981a; Muzet et al., 1983; Sagot et al., 1987; Libert and Bach, 2005), as demonstrated in Fig. 5. In NREM stages of sleep, when thermoregulatory processes are active, both skin temperatures and sweating rates rise with increasing ambient temperatures (Libert and Bach, 2005).

The lower sweat rates during REM sleep than in other stages of sleep could explain the differing skin temperature results found by Henane et al. (1977) and Haskell et al. (1981a) mentioned above. Henane et al. (1977) found that the skin temperature could rise as much as 2 °C during REM sleep, whereas Haskell et al. (1981a) measured a rise of only 0.1 °C. Henane et al. (1977) used a wind speed of 0.15 m/s, compared to 0 m/s in (Haskell et al., 1981a). A positive air velocity could lower the skin temperature of a semi-nude uncovered sleeping subject during non-REM sleep periods through the mechanism of convection, when the sweat rate is higher, increasing the difference between the skin temperatures during REM and non-REM sleep. This is an important consideration when investigating the influence of ambient and skin microclimate conditions on sleep quality.

4.5. Summary

Researchers have shown that changes to TST and to the various sleep stages can reduce sleep quality and hamper the restorative processes normally enabled during sleep. Thermoregulation is greatly reduced during REM sleep, so extremes of temperature and humidity in the sleep environment and especially in next to skin microclimate, can significantly affect homeostasis and hence sleep quality. Similarly, lower sweating rates during REM sleep inhibit the body's ability to thermoregulate and to respond to changed surrounding thermal conditions. Skin temperature changes across different phases of sleep and depends upon the environmental conditions, especially those immediately surrounding the skin. Because skin temperatures during sleep can substantially affect sleep quality, stable ambient and bedding microclimates will support better sleep patterns. Therefore, the thermal properties of bedding at different ambient temperatures are important for maintaining an optimal sleeping microclimate, which will enable skin temperatures remain at thermoneutral levels, and achieving quality sleep. To the best of our knowledge, there are no published studies of the effects of bedding microclimates on body temperature and sweating, or studies that characterise these microclimates.

5. External factors and sleep quality – the thermal environment

Extremes of temperature in the sleeping environment are a cause of sleep disruption (Carskadon and Dement, 2005) and can elicit arousal in every sleep state (Parmeggiani, 1986). As summarised above, the total sleeping environment, which includes the air temperature, humidity and the bedding microclimate, influence sleep quality by affecting the skin temperature and its stability. In addition, the thermal load on the body can be influenced by other factors, such as body mass, age and menstrual cycle. In some studies (Haskell et al., 1981b; Pan et al., 2012; Lan et al., 2014) high air temperature was found to disrupt the wake–sleep cycle and reduce TST, as well as decrease the length of REM and SWS and delay sleep onset (Haskell et al., 1981b; Sewitch et al., 1986; Carskadon and Dement, 2005). More specifically, the thermal environment can affect the frequency and length of both NREM and REM phases (Parmeggiani, 1980, 1986: Sewitch et al., 1986; Bischof et al., 1993). For example, a mild negative thermal load may increase the total duration of NREM stage 4 sleep (Sewitch et al., 1986). Bigger thermal loads can cause partial or total SD (Parmeggiani, 1986).

Candas et al. (1982) showed that when the skin temperature of semi-nude subjects without covers in an environmental chamber increased by 0.8 °C/min, 50% of the subjects woke. Thirty per cent of waking subjects woke during SWS, and 66% during REM sleep. Sleep interruption was similar for changes in temperature of + 1.6 °C and − 0.8 °C (Candas et al., 1982).

Hot environments have been found to disrupt sleep significantly,

Table 3
Sleep parameters under different environmental conditions (source: Tsuzuki et al., 2004).

Total duration of sleep time (%)		
	26 °C, 50% RH	**32 °C, 80% RH**
Wake	3.69 (1.87)	20.43 (17.13)*
Stage 1	8.76 (4.24)	1.81 (5.91)*
Stage 2	47.01 (9.89)	37.43 (12.95)*
Stage 3	6.68 (9.89)	5.77 (4.26)
Stage 4	9.46 (5.20)	5.39 (5.46)*
Stage 3 + 4	16.13 (8.59)	11.16 (9.32)
REM	21.36 (4.97)	17.77 (5.83)
MT^{a}	0.02 (0.05)	0.07 (0.08)*
SEI^{b}	93.28 (3.40)	78.16 (17.98)*

a = moving time, b = sleep efficiency index.
* $p < 0.05$.

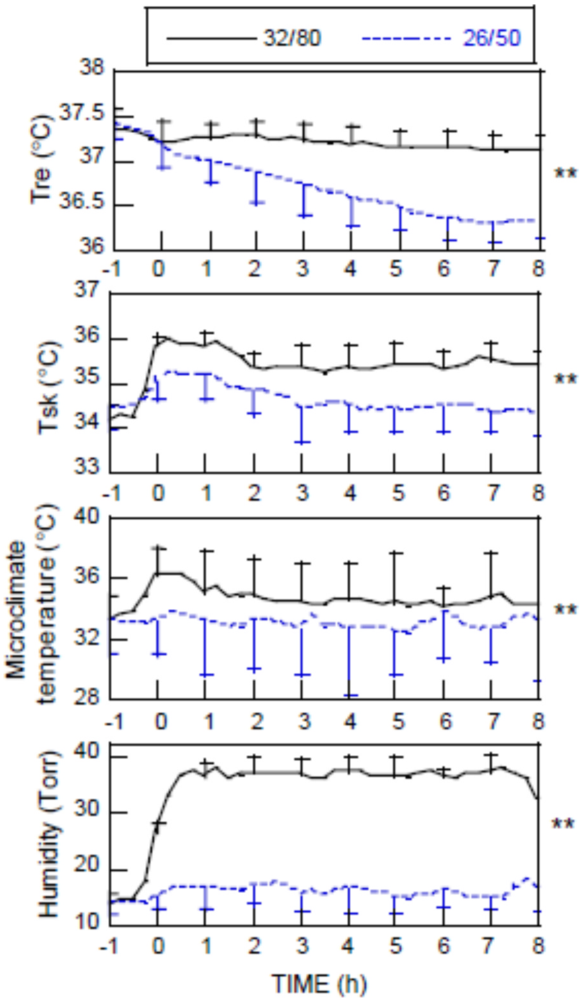


Fig. 6. Time course of "average rectal temperature (Tre), mean skin temperature (Tsk), microclimate temperature and humidity during 8 h night sleep under 26°C/50%RH (- – –) and 32°C/80%RH conditions (—). Values are means with SD (n = 9). (**) represents statistically significant difference at $P < 0.01$. Nine male volunteers participated in the study where the experiments were carried out from August to September using two climate chambers. The subjects were asked to sleep and wake on a regular schedule and slept wearing briefs, short pants, and short sleeve pyjamas (100% cotton) on a bed covered with a bed sheet (100% cotton) and a blanket (100% cotton). Clothing insulation was estimated to be 0.4 clo" (Tsuzuki et al., 2004, p. 33).

with common impacts being increased wakefulness and reduced amounts of NREM and REM sleep (Karacan et al., 1978; Tsuzuki et al., 2004; Okamoto-Mizuno et al., 2005). For example, Tsuzuki et al. (2004) studied the sleep efficiency of subjects in two sets of environmental conditions: 26 °C & 50% relative humidity (RH) (26/50) and 32 °C & 80% RH (32/80). The nine healthy male subjects wore pyjamas and were covered with a cotton blanket during sleep. Periods of wakefulness and stage 1 sleep were significantly longer at 32/80 than 26/50 (Table 3); however, in all other stages of sleep – that is, stages 2–4 and REM – sleep duration was shorter in 32/80 (Tsuzuki et al., 2004).

In addition, at 32/80, subjects had a significantly higher mean heart rate and sweat rate, as well as higher mean rectal and skin temperature than at 26/50 (Fig. 6). Microclimate temperature and relative humidity conditions (i.e. between the skin and the pyjamas) were significantly higher in 32/80 (Tsuzuki et al., 2004) and subjects had markedly lower sleep efficiency and significantly higher wakefulness duration over the nights of sleep (Table 3). However, whilst the subjects wore pyjamas and were covered with bedding, this study did not investigate their influence on the sleep microclimate.

The results of the aforementioned studies, both in cold and hot environments, show that it is important to have sleepwear and bedding which ideally keep the sleeping microclimate in the approximate range of 30–32.5 °C. The sleeping system (i.e., bedding, sleepwear and mattress) should also prevent rapid changes in skin temperature, even if the ambient temperature changes rapidly, to promote quality sleep.

As noted, little research has been conducted on conditions in the microclimate sleep environment (Tsuzuki et al., 2004; Lan et al., 2017), with most studies focusing on ambient conditions and their effect on sleep. There is a clear need to understand how sleeping systems compare in their ability to support microclimate temperature and humidity levels and moderation of their changes during sleep. It is also important to determine the sleepwear and bedding combinations that provide an environment that supports sleep quality.

6. Effect of bedding assemblies and clothing on sleep

As discussed in earlier sections, thermal comfort during sleep is primarily linked to the bedding microclimate, with ambient conditions a secondary factor (Bischof et al., 1993). The few studies that have considered bedding and sleepwear have found that sleep patterns are more susceptible to disruption with exposure to heat than cold (Okamoto-Mizuno and Mizuno, 2012). Muzet et al. (1984) suggested that bedding limits temperature changes in the sleep environment and therefore supports normal sleep stages and cycles. This reinforces the idea that appropriate bedding and sleepwear is essential for an optimal sleeping microclimate and good sleep quality (Okamoto-Mizuno and Mizuno, 2012).

As noted earlier, most studies have excluded the impact of bedding and sleepwear on sleep, the sleep microclimate and sleep quality, focusing on nude or semi-nude subjects and therefore eliminating crucial real-life dynamics (Okamoto-Mizuno and Mizuno, 2012). For example, to the best of the authors' knowledge, no published studies have assessed the different types of bedding and sleepwear in a given sleeping environment. In addition, no studies have fully assessed how bedding and sleepwear influence microclimate skin temperature or humidity levels during sleep. Overwhelmingly, sleep studies have involved human subjects, making it impossible to objectively assess bedding and sleepwear performance.

Studies of the effects of sleeping environments on sleep quality have compared different kinds of blankets, quilts and other covers. For example, the use of an electric blanket which heated the bedding microclimate temperature to 39 °C reduced TST, with the same mean duration per REM episode but fewer episodes (Bach et al., 2002; Kräuchi and Deboer, 2011). Some studies have involved blankets and varied both ambient temperature and humidity (Tsuzuki et al., 2004, 2008), but no known study has assessed the impact of the full bedding microclimate on sleep quality.

In a real-life sleep situation (using a blanket, quilt or similar cover, and sleepwear), sleep is more often disrupted due to heat than cold exposure (Karacan et al., 1978; Tsuzuki et al., 2004). Multiple experiments with blankets have shown ambient temperature (ranging from 3 °C to 23 °C) to have little effect. Greater negative effects on sleep quality have been measured during hotter ambient temperatures under real-life sleeping conditions (Tsuzuki et al., 2004). It has been reported that the bedding microclimate temperature is less affected at colder temperatures than hotter ones (Okamoto-Mizuno and Mizuno, 2012), which supports the proposition that studies of bedding microclimate influences on sleep should focus on high-temperature ambient conditions.

According to Rohles and Munson (1981), sleep environment temperatures of 10.0 °C, 21.1 °C and 32.2 °C did not greatly affect sleep quality when using conventional bedding and the subjects' standard sleep clothing. However, at an ambient temperature of 32.2 °C, the subjects' mean skin temperature was 35.6 °C, compared to 34.5 °C at ambient temperatures of 10.0 °C and 21.1 °C, and as discussed earlier, higher skin temperature is strongly associated with poorer sleep quality. (Note that whilst this study included bedding and sleepwear, their type and composition were largely unidentified, preventing a clear understanding of their impacts on the findings.)

Bischof et al. (1993), studying five human subjects, found that local microclimate temperatures (between sheet and mattress) can vary widely. They described one subject observed in an ambient temperature of 24 °C; the under-sheet temperature in the left pelvis region was around 35 °C, while in the right pelvis region it was around 25 °C (Fig. 7). These results show that large differences in temperature can exist within the bedding microclimate; however, a more comprehensive approach would be to study the entire bedding environment. This study (Bischof et al., 1993) also illustrates the wide variation in results that can occur in human trials, even under the same ambient conditions.

7. Testing methods used in sleep studies

7.1. Human testing

Sleep research most commonly involves human subjects, and is conducted with various methods. Many studies have used controlled environmental chambers in which the subjects sleep. The temperature, humidity and air flow in these chambers can be controlled to allow for either stable ambient conditions or transient conditions that imitate the changes in conditions encountered across a night of sleep (Henane et al., 1977; Rohles and Munson, 1981; Muzet et al., 1983, 1984; Sagot et al., 1987; Bischof et al., 1993; Tsuzuki et al., 2004; Okamoto-Mizuno et al., 2005; Leung and Ge, 2013).

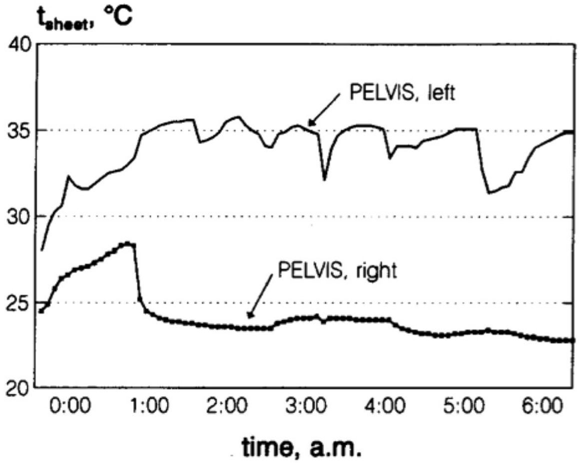


Fig. 7. The under-sheet microclimate temperatures in the pelvic region of a sleeping subject, for an ambient temperature of 24.0 °C, without spot cooling of the head (reproduced from Bischof et al., 1993). "Each of 5 healthy participants (2 female and 3 male, 23.4 ± 2.4 years) slept 5 nights in a climate chamber. While the first night was used for adaptation to the experimental conditions, 2 nights with uniform climate (top = 24 °C) and 2 nights with a slight spot cooling of the head (tspot = 20 °C, v < 0.1 m/s) followed. The subjects used bedspreads and pyjamas with thermal insulation of 0.8 clo" (Bischof et al., 1993).

Several approaches are used to measure sleep cycles and quality. PSG is considered a gold standard for evaluation of sleep quality and quantity (Halson, 2013b) and is used to capture brain waves through electroencephalography; eye movements can be monitored and recorded using a video graphic record via electrooculography, and chin muscle tension and heart rhythms can be recorded using electromyograms (Haskell et al., 1981b; Lee and Park, 2006). PSG provides information for determining sleep state and processes, such as TST, SOL, SE and duration of sleep stage (i.e. stages 1–4 and REM) (Krystal and Edinger, 2008). PSG involves attaching electrodes to the scalp and face of the subjects (Lee et al., 2004; Buguet, 2007; Lan et al., 2017).

Actigraphy allows 24-h recording of body movement via a device worn on the wrist (Morgenthaler et al., 2007). The actigraph is more limited than PSG as it cannot categorise sleep phases, only recording quantity of sleep, such as TST, SOL, and SE. Further, as actigraphy monitors movement, it cannot distinguish between motionless wake periods and sleep episodes. However, actigraphy is still considered beneficial for understanding sleep, as it is non-invasive and enables easy collection of data over periods of two weeks or more (Halson, 2013b).

Time-lapse photography (Dickson, 1984), a television camera (Haskell et al., 1981b), and video footage (Tsuzuki et al., 2008) have all been utilised to monitor the sleeping positions of subjects.

During sleep, a subject's rectal or oesophageal temperature, which correlate strongly with core temperature (Lefrant et al., 2003), and skin temperature can be measured using thermocouples or thermistors (Bach et al., 2002).

Self-report questionnaires are subjective techniques for measuring sleep quality (Lan et al., 2017), and are frequently used for large samples of human subjects. An example is the PSQI (mentioned earlier), which evaluates sleep patterns over a one-month timeframe (Buysse et al., 1989) to identify any sleep disorders and disturbances (Mollayeva et al., 2016). The PQSI measures seven aspects of sleep, and provides a global sleep quality score (Buysse et al., 1989).

Multiple methods have been used to measure sweating during sleep, including weighing subjects before and after sleep, and measuring any urine output (Okamoto-Mizuno et al., 2004; Tsuzuki et al., 2004). Continuous weighing of subjects across the entire night (Henane et al., 1977) assumes that most of the weight loss is due to sweat. A more direct approach to sweat loss measurement is the use of sweat-collecting capsules along with a dew-point hygrometer (Muzet et al., 1984; Sagot et al., 1987). Other researchers estimated total weight loss, including water loss through respiration, concluding that water loss through respiration is a significant part of total water loss during sleep (Weissenberg, 2005).

Human studies in sleep, similar to other fields of thermal biology, are typically constrained by cost; high variability between participants; extensive ethics compliance and logistics of experiments, such as requirement for participants to sleep in foreign environments using disturbing sleep monitoring equipment and others. That is why most studies to date have involved fewer than 10 subjects, with the largest known published study using ECG in an environmental chamber having 16 (Lee and Park, 2006). These small samples lead to high variation in data and decrease the applicability of the results to the general human population. Therefore, objective studies involving sophisticated instruments and methods would be of substantial support to human trials.

7.2. Sleep-related research using a thermal manikin

Very few studies have used an instrumented thermal manikin; a recent review of research on thermal sleep environments (Lan et al., 2017) cited only one (Lin and Deng, 2008). These researchers measured the thermal resistance of a wide range of bedding systems, including blankets and quilts, as well as sleepwear (Lin and Deng, 2008). They set the thermal manikin's hands and feet at 31 °C and the other body segments at 35 °C, whereas the sleep physiology research reported earlier (Kräuchi et al., 1999) shows that, when asleep, proximal and distal skin temperatures are approximately equal. In addition, evaporative resistance was not assessed, so the study provided an incomplete and very likely erroneous picture of the sleep microclimate. Other studies (McCullough et al., 1987) have focused solely on measuring the thermal insulation of bedding with a view to increasing thermal insulation values (Lin and Deng, 2008).

There are methods for the determination of the thermal resistance of individual components of bedding systems (e.g. mattresses), such as ISO 8302 (International Organization for Standardization, 1991), which measures the steady-state heat transfer through flat slab specimens. However, there are no standard methods for the determination of the thermal performance attributes of bedding systems as a whole, so researchers utilise the methods designed for testing of apparel or sleeping bags.

Most sleep-related research using thermal manikins has been directed at the measurement of the thermal and evaporative resistance of sleeping bags. These studies were carried out in environmental chambers with varying temperature, humidity and air velocity. The use of thermal manikins to measure thermal resistance and insulation is also a standard technique used by sleeping bag manufacturers, based on two standards, EN 13537 (European Committee for Standardization (CEN), 2002) and ASTM F1720 (American Society for Materials and Testing, 2011). Some publications representative of this research are Huang (2008), Wu and Fan (2009) and Lin et al. (2013). Similar to the measurements of thermal resistance in apparel, these measurements are taken in steady state conditions and give no information on the characteristics of the next to skin or in-bedding microclimates through the different stages of sleep, neither in static nor in dynamic conditions.

Use of thermal manikins to measure factors related to sleep other than the thermal resistance and insulation of bedding systems, including sleeping bags, is rare; to the best of the authors' knowledge, there is only one fully developed method that evaluates the micro-environment temperature and humidity characteristics of entire bedding systems (Troynikov et al., 2015). There is considerable potential for the use of thermal manikins in investigating the role of sleepwear and bedding on the quality of human sleep.

Thermal manikins have significantly fewer variables than human subjects, and permit many repetitions of tests for greater result validity, control of variables and manikin settings, and for use in extreme environments conditions (Celcar et al., 2008; Wang and Lee, 2009; Wang and Li, 2016) – often difficult with human studies for practical reasons. Further, manikin studies do not require ethics approval, which is mandatory for human studies (Cann et al., 2005).

However, similar to the use in apparel thermal research, thermal manikins have a number of disadvantages: they are limited in close replication of human sleeping behaviour, such as change of sleeping posture, consciously or subconsciously, partially or fully removing bed covers when excessively hot and are unable to be operated in a mode replicating human thermoregulation during sleep. Various mathematical models are currently available for modelling the human thermal and comfort responses during active physical activities (Psikuta et al., 2017), especially in hot environments, however, there are no such models available for the human sleep.

8. Conclusions

Human sleep has been studied extensively, yet is still not fully understood. However, it is clear that adequate sleep time is important for human health and wellbeing to achieve optimal performance and provide efficient recovery.

Investigations of the results of sleep loss have produced evidence of detrimental effects on human health and performance that include reduced cognitive performance and psychomotor skills, impairment of mood, heightened fatigue, reduced time to exhaustion and decreased vigour, with resultant loss of power during performance of tasks and physical activities. In addition, decision-making is impaired, and the speed and accuracy of task performance are reduced by poor sleep quality.

Further, studies have shown that sleep plays a key role in recuperation and recovery. Growth hormones released during sleep are thought to stimulate and boost the immune system, assisting tissue growth and recovery from injury, which is an important part of the recuperation process. All of these factors can adversely affect human health and wellbeing, supporting the premise that optimal sleep patterns promote optimal performance. Specifically, the literature contains many calls for more research into athletes' sleep and sleep's effects on athletic performance and recovery, to enable greater understanding of thermal biology in relation to athletes and other physically active people.

Skin temperature, its rate of change, and sweating during sleep can significantly affect sleep quality, implying that stable ambient and/or bedding thermal microclimates support good sleep patterns. It follows that the thermal properties of bedding, both in steady state and transient temperature conditions, are important for achieving quality sleep, and therefore that there is a need to characterise optimal sleeping thermal environments and bedding systems for high-quality sleep. However, knowledge of the effect of different types of sleepwear and bedding materials on the sleep thermal microclimate – and the effect of such sleeping systems on sleep – is lacking. To the best of the authors' knowledge, no study has combined the effects of body temperature and sweating on sleep quality when considered in conjunction with the microclimate of the sleeping system. Research designed to produce greater understanding of these aspects is warranted.

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Declarations of interest

None.

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