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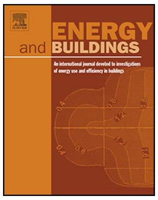

The importance of temperature and thermoregulation for optimal human sleep

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ABSTRACT

In the last few decades, there has been a decline in average sleep duration and quality that has adversely affected general health of the population. Increased use of artificial lighting, television, noise, and light emitting gadgets in the post-industrial society has led to an environment full of factors that can adversely affect sleep. Sleep is essential for the restoration of health and well-being, and has a direct effect on the quality of life of an individual. It is thus imperative to design constructions that provide a sleep permissive environment. In addition to environmental factors, sleep and wakefulness in humans is affected by a multitude of physiological parameters as well. The mechanisms and interplay between these factors that influence sleep permissiveness or promotion have received relatively little attention. The present review takes a holistic approach in explaining the basic circadian and homeostatic processes that influence sleep and sleepiness, and then delves deeper into how the thermal rhythms of the body affect these processes. It also discusses previous research and models in construction design that influence ambient temperature, skin surface temperature, and other thermoregulatory factors that can be controlled for optimal sleep.

1. Introduction

There are several environmental factors that can affect the quantity and quality of sleep. A sleep environment is affected by at least six physical factors including noise, light, temperature, humidity, air circulation, and settings (beddings, pillows etc.) and psychological factors such as safety and stress. Light is one of the most important factors since it is the external time cue (zeitgeber) for our 24 h biological clock that promotes sleep and wake at different times of the day and night. Light also has an immediate stimulatory effect. Noise is defined as unwanted sounds that one is exposed to during the day and night. The effect of noise on sleep may vary with individual sensitivity, age, and personality. While all these factors are important in good sleep hygiene, temperature is arguably the most important determinant in sleep quality that is left uncontrolled, and that is strongly linked to physiological mechanisms regulating sleep. Changes in environmental ambient temperatures from hot to cold can affect sleep even in healthy humans without insomnia or other sleep disorders [1–3]. Reduced sleep quality and quantity has been associated with reduced quality of life and many adverse health effects including chronic conditions like type 2 diabetes [4–7], respiratory disorders, hypertension [5,7,8], obesity [9,10], quality of life [11], and increased mortality [12–18].

Effects of poor sleep quality become more pronounced as people begin to age [19–23] with reduced functional capabilities [2,19,24] and increased use of medication [24,25] leading to greater use of health services [26,27]. In a prospective study conducted on a cohort of 185 healthy older adults (aged 55 and above), after controlling for age, gender and medical burden, risk of death was found to be nearly doubled in subjects with sleep latencies higher than 30 min, and sleep efficiencies less than 80% (percentage of time spent asleep during polysomnography) [1]. Another study with 272 subjects at a geriatric hospital also reported insomnia and sleep onset delay to be associated with increased mortality risk [3].

Based on several epidemiological studies, obesity is an outcome of poor sleep quality that affects individuals across age groups [9,10,28–31]. In a prospective sleep duration study with a cohort of 496 young adults conducted over a period of 13 years, shorter sleep duration was found to be associated with obesity and weight gain [2]. A meta-analysis of 45 sleep studies from across the world with a cumulative subject count of 634,511 adults belonging to age range of 2 to 102 years also supports this association. Other variables that influence include obesity, with overweight subjects 60–80% more likely to be short sleepers in both children and adults [32].

The thermal environment while sleeping is a key factor since physiological thermoregulation has been strongly associated with

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mechanisms regulating sleep. The thermal environment is especially important because it can be artificially modulated to promote sleep permissive conditions. Understanding of thermophysiology and its relation to sleep leads to the hope that high quality sleep environments can be created through use of multiple technologies including heating, ventilation and air conditioning that allows for energy efficient environmental control while maintaining thermal comfort. Temperature related interventions in sleep environments will help alleviate sleep disturbances, and help manage the sleep and alertness problems faced by the general population.

2. Sleep and thermoregulation

In the field of sleep research, the main focus has been on the modeling of the underlying circadian and homeostatic processes. The circadian component is part of an endogenous biological clock that controls or influences a wide range of molecular, physiological, and behavioral processes, including the promotion of sleep in one part of the circadian cycle (night) and wakefulness in the other part (day). The suprachiasmatic nucleus (SCN) located in the hypothalamus is the master control region for this circadian clock. In contrast, the homeostatic component of sleep is simply dependent on previous sleep or wake. The longer someone stays awake, sleep need and your sleep debt increases steadily, increasing the pressure to sleep, although this can be opposed by the circadian system making us sometimes feel wide awake at night, despite the increased sleep need. This sleep pressure or need dissipates during sleep, and the cycle starts again after waking up.

The core body temperature also has a cyclic nature that is governed by both the sleep wake cycle and circadian rhythms. The regulation of sleep-wake cycles and rhythms of body temperature changes is tightly coupled [33,34]. During sleep onset, metabolism is reduced and heat loss is accelerated leading to an integrated fall in body temperature. The mechanisms of thermoregulation during both wake and sleep are the same except that the internal thermostat has a lower set point while sleeping and the body maintains and defends it during sleep.

During the nocturnal sleep phase, the core temperature decreases, and then begins to increase during the early waking phase [35]. The core consists of abdominal, thoracic, and cranial cavities that contain the vital organs. The core is able to retain or dissipate heat through the shell that consists of skin, subcutaneous tissues and muscles. Shell or peripheral skin temperature is where any decrease or increase in core body temperature must begin. Therefore, for the core to drop one degree centrigrade (or two degrees Fahrenheit) as is typical during sleep onset, the peripheral skin temperature on the hands, feet, cheeks, etc. will typically increase.

2.1. Physiological thermoregulation

The conductive and convective heat transfer from body surface to the environment helps bring about the decrease in core body temperature at sleep onset. Changes in core temperature are typically achieved via changes in skin surface blood flow through arteriovenous anastomoses that are connections between arteries and veins. They adjust blood flow to skin, especially the hands and feet, and can dilate to lose heat or constrict to conserve it [36,37]. While reduction in body temperature is an important parameter to let the body enter a sleep permissive state, in the presence of higher ambient temperatures, the reduced shell temperature is maintained through modulation of sweat rates in later stages of sleep. In high ambient temperatures, along with increased sweating, tachypnea (rapid breathing) is also observed. In low ambient temperatures, shivering thermogenesis occurs, at times, in combination with piloerection. During heat exposure, in the initial segment, sleep quality is reduced because of sleep disruptions and increased latency. These effects are overcome in the later segment of sleep, possibly because of increased sleep demand. Humid heat exposure has even more pronounced effect with increased wakefulness in both initial and later segments of sleep. In mammals, a rise in body temperature has been associated with increased blood pressure and heart rate. The increased body temperature by elevated heat exposure leads to more body movements during sleep. Increase in body movement is associated with fragmented sleep since mobility during sleep is accompanied by frequent awakenings.

2.2. Behavioral thermoregulation

In both heat and cold exposure, along with physiological adjustments, behavioral thermoregulation also takes place [38,39]. The behavioral thermoregulation is geared towards regulating the convective heat loss that can lead to faster increase or decrease in shell temperature while going to sleep. It is mostly driven by ambient temperatures leading to changes in areas of body covered by bed covers or clothing and/or contact area of the body with the mattress. Neck, shoulder and upper extremities have higher sensitivity as compared to lower extremities and the trunk. In heat exposure, lateral body position increases, possibly because of reduction in the contact area with the mattress. Prone or supine positions are more prominent during cold exposure. Fans and other air conditioning equipment allow for the modulation of both conductive and convective heat transfer to achieve and maintain the thermal comfort in the sleeping environment.

2.3. Thermal comfort

There are two aspects to the thermal comfort, one is physiological that is intrapersonal and the other is bioclimatic which deals with the environment. A *physiological* thermoneutral or a thermal comfort zone is defined as the range of ambient temperatures when resting metabolic rate of the body is minimal and constant. Within this range of temperatures, the body does not need to make any effort to maintain thermal homeostasis since the heat produced with this minimal metabolic rate is balanced by the heat loss to the environment. The thermoneutral temperature inside the sleep microclimate lies around 30 °C [40], with 28 °C to 31 °C being the thermal comfort zone for most humans. In a study carried out in semi-nude, uncovered subjects, temperatures of 26 °C and below caused increased sleep disruptions and cold discomfort with increased REM and NREM sleep latency. Given more typical bedding, 19 °C was found to be the preferred ambient room temperature and deviation from this temperature was accompanied by subjective discomfort [34,41]. In another study with subjects under covers during sleep, the ambient temperature was kept at 13 °C, and the microclimate temperature inside the covers was 26 °C, similar results with increased nocturnal awakenings were seen [42]. Real life studies in extreme ambient temperatures of the arctic have also shown similar results [43]. This suggests that the lower end of the human thermal comfort zone for sleep falls around 27 °C, however, to achieve this temperature may require a considerably lower ambient temperature. Increases in ambient temperatures often lead to sleep disruptions and reduced REM sleep.

2.4. Bioclimatic thermal comfort zone

According to the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) standards, “thermal comfort is that condition of mind that expresses satisfaction with the thermal environment” [44]. The satisfaction can be considered as an output of cumulative effect of an individual's physical, physiological, psychological and other processes. It can be defined as a range of climatic conditions where majority of people (at least 80%) do not feel thermal discomfort by either hot or cold conditions.

Macpherson, in his review of methods for assessment of thermal environment has identified six factors that affect thermal sensation. These factors are air temperature (T_a), humidity (P_a), air speed/velocity (V_a), mean radiant temperature (T_{mr}), metabolic rate (M), and clothing levels. The Fanger's thermal Comfort Equation (documented in ISO7730) is the most commonly adopted concept for thermal comfort in designing living and work environments [45].

The basic equation for energy balance between body and environment, per unit surface area, is written as follows (Eq. (1)):

$$S = M - W_k - E_{sk} - E_r - C - R - C_k \tag{1}$$

S = Energy balance of human body; M = Metabolic Rate; W_k = External work; E_{sk} = Heat loss from skin; E_r = Heat loss via respiration; C = Heat loss from surface of clothed body to air; R = Heat loss by radiation from surface of clothed body to environment; C_k = Heat loss by conduction via skin contact.

The mean radiant temperature is equally important as the air temperature itself. Since it is difficult to obtain the absolute value of mean radiant temperature because of the presence of gradients and local thermal discomfort, several integrating parameters have been included in the Fanger's equation. Three of these integrating parameters are Effective temperature (T_e), Operative temperature (T_o), and Equivalent temperature (T_{eq}). The Effective Temperature is the temperature of an imaginary enclosure at 50% relative humidity at which the heat exchange is similar to what seen in the actual environment the person is in. It integrates the effects of T_a, T_{mr}, and P_a. The Operative temperature is an integrated effect of T_a and T_{mr}. It is the temperature of an imaginary enclosure where dry heat exchange by radiation and convection is same as in the actual environment. The equivalent temperature is an integrated effect of T_a, T_{mr}, and V_a.

Based on the results from 1300 subjects for a thermal sensation scale, Fanger proposed a thermal comfort index called Predicted Mean Vote (PMV), which can be represented by the following equation (Eq. (2)):

$$PMV = \left(0.0303e^{-0.036M} + 0.028\right)\left\{\begin{array}{l} (M-W) - 3.05\times10^{-3}\,[5733 - 6.99\,(M-W) - P_a] \\ -0.42\,[(M-W) - 58.15] - 1.7\times10^{-5}M\,(5867 - P_a) \\ -0.0014M\,(34 - T_a) - 3.96\times10^{-8}F_{cl}\left[(T_{cl}+273)^4 - (T_{mr}+273)^4\right] \\ -F_{cl}\times H_c\,(T_{cl}+T_a) \end{array}\right\} \tag{2}$$

M = Metabolic Rate; W = External work; P_a = Humidity; T_a = Air temperature; T_{mr} = Mean Radiant Temperature; F_{cl} = Ratio of surface area clothed/nude; T_{cl} = Surface temperature of clothing; H_c = Convective heat transfer coefficient.

According to the standards based on Fanger's equation, it is essential that in terms of humidity, the air should not exceed sultriness limits; air speed limits should be closely defined; stratification of air temperatures between head and ankle should be less than 2 °C; minimum difference between air and radiant temperatures; minimum difference in radiant temperatures in different directions; and perceived temperatures in different parts of the room should not change by more than 0.8 °C.

2.5. Environmental thermoregulation

As mentioned earlier, besides light and noise, thermal environment is the most critical parameter that can be modulated to improve sleep quality. The variables in the Fanger's equation can be modulated to the human body during sleep with respect to the thermal environment. The traditional unit for measurement of metabolism is Met where 1 Met = 58.15 W per square meter of body surface. An average human body has surface area of 1.7 square meters which means heat loss of 100 W at activity level of 1 Met. During sleep the metabolism is at its lowest at 0.8 Met. The clothing is classified according to its insulation value (clo) with a naked body having a clo of 0. A typical night suit has a clo of 0.2. Based on this information, Lin and Deng have developed a thermal comfort model for sleep environment in the subtropics [46]. A theoretical analysis by Maeyens et al. for summer bedroom temperatures suggests input parameters for Fanger's equation as: metabolic rate at 0.7 Met, relative humidity at 55%, air speed of 0.01–1 m/s, and clo of 0.8 [47]. The clo of 0.8 is the combined clothing index of sleepwear, sheets, mattress and pillow. In Chartered Institution of Building Services Engineers (CIBSE) Guide [48], data collected in UK indicated sleep quality as a function of bedroom temperature [49]. The data suggests sleep quality decreases above 24 °C, but ASHRAE and CIBSE guidelines indicate this temperature can be increased to 27 °C with use of fans [44,48].

3. Discussion

An increase in both heat and cold exposure has negative effects on the overall sleep quality, but it seems that the range of temperatures that the body can adapt to while sleeping is less in the case of cold exposure as compared to heat in exposed people, but is likely the reverse in conditions with sufficient insulation (e.g. blankets). Previous research in uncovered individuals suggests that cold exposure leads to increased sleep disruptions and has a greater effect than heat exposure. A major challenge in studying the effects of ambient temperatures on sleep is that even though cold temperatures have been shown to increase wakefulness as compared to higher temperatures, in real life, the presence of clothing and covers makes it easier to maintain temperature inside one's microclimate in colder ambient temperatures as compared to hot environments.

Though models for sleep environments have been built by modifying the Fanger's equation, it is important to remember that a thermal comfort for sleep environment is very different from any place that individuals dwell in while awake. Our bodies are at a disadvantage during sleep because of limitations in physiological and behavioral responses to external environment. In addition to this, the data for sleep environments from different parts of the world are indicative of the variation in physiology and lifestyles of individuals within those populations. These variations within populations are expected given that they have evolved over generations that have adapted their physiology and behavior according to the surrounding environments. In addition to the subjective vote, future sleep environment models should be based on population stratifications that also take into account the physiological, geographical, and lifestyle parameters of the subjects. As we gain more knowledge about sleep with advances in the biomedical sciences, it should eventually be possible to include genetic parameters in these models [50,51].

With an increase in sleep research, there has been a growing awareness about the importance of having the right quantity and quality of sleep. Smartphone apps used either as standalone approaches, or in combination with portable EEG systems, with their ability to detect and log sleep quantity and quality, are accelerating progress in this growing area of interest. Being able to monitor sleep over a period of time could help improve diagnoses while reducing cost of research and treatment, and help people to educate and understand their own trends and sleep needs. However, use of these tools won't be effective unless the consumers are empowered with options to personalize and enhance their sleep experience. There is a certain level of awareness about the quality of one's mattress, surrounding noise levels, and ambient light, but very limited importance is given to ambient temperature and its relation to biological mechanisms. It has been suggested that a time memory for heat or cold exposure exists in the human thermoregulatory system that might have an entrainment effect leading to autonomic core temperature changes based on the previous exposure without any alterations of external temperature [52]. Along with better mattresses and intelligent ambient lighting products, adaptive means of providing proper effective temperature might be the sleep aid of the future.

There are many ways to control thermal comfort; however, some methods are more suited to automated control in the sleep environment. Personal parameters such as clothing level (clo) and metabolic rate (met) are obviously outside of the realm of automated control. Other parameters are more suitable for less obvious reasons. Radiant thermal control can be a very efficient means of thermal comfort control; however, this method is usually prohibitively expensive to install in a home environment. Air temperature and humidity are the most common methods of active thermal comfort control in the home; however, it has some downfalls. It is very energy intensive to control temperature and humidity in the sleep environment when controlling that one zone also requires conditioning all other zones in the home (occupied or not). Additionally, control of temperature and humidity can be a very slow process (due to hysteresis and deadband of typical systems). If active control based on sleep state feedback is desired, then an HVAC system may not be able to react quick enough to avoid thermal disruptions [44]. Airflow has the added benefits of being very fast reacting and low energy; however, low temperature disruptions cannot be avoided with airflow alone. An energy efficient active sleep comfort control system would likely need to consist of a combination of fast reacting airflow adjustments and slower reacting full room temperature adjustments. Including parameters of noise and ambient light, developing a personalized thermal sleep comfort model based on the personal preferences of clothing and temperatures might be useful in developing algorithms for smart devices that can regulate thermal environment in real time.

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