Building and Environment 99 (2016) 252–259

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Ten questions concerning thermal environment and sleep quality

Li Lan, Zhiwei Lian*

Department of Architecture, School of Naval Architecture, Ocean & Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form
19 January 2016
Accepted 20 January 2016
Available online 22 January 2016

Keywords:
Thermal comfort
Indoor air temperature
Air flow
Thermal environment
Sleeping environment
Sleep quality
Sleeping people

ABSTRACT

People spend about one third of their lives sleeping. Sleep is essential for the recovery of the body from both physical and psychological fatigue suffered throughout the day, the refreshment of mind, and the restoration of energy for maintenance of bodily functions. Current thermal comfort theories and standards are mainly concerned with people in waking state. However, many problems regarding thermal environment are found within a few field surveys in bedrooms, pushing out the need to investigate thermal environment and thermal comfort for sleeping people. In this paper, the questions concerning the measurement and evaluation of human sleep quality, the correlation between thermal regulation system and sleep regulation, and the characteristics of night-time space cooling load etc. are answered. The evidences illustrating the effects of thermal parameters on human sleep quality are also provided, in an attempt to shed light on the thermal comfort requirements of sleeping people.

1. Introduction

People spend about one third of their lives sleeping. Sleep is essential for the recovery of the body from both physical and psychological fatigue suffered throughout the day, the refreshment of mind, and the restoration of energy for maintenance of bodily functions [1]. Poor sleep quality impaires cognitive performance in older adults [2], and impacts brain function related to reward processing, risk-taking, and cognition in adolescents [3]. Disturbed nocturnal sleep also has consequential effects on health, increasing the risk of obesity, type 2 diabetes and cardiovascular disease [4,5].

Many factors, such as health states, emotional states, bedding conditions, and thermal environments affect sleep quality, with thermal environment being one of the most important factors [6,7]. The issues of thermal comfort in office buildings in different climates have been studied by several researchers and are well documented in the scientific literature [8]. However, the definition of sleep thermal comfort and the relationship between sleep efficiency and sleep thermal environment have not been well-established in current literature. While there are many studies on thermal environment implication to psychological and physiological responses during sleep, most are in relation to medical conditions or necessities, such as sleep deprivation thermal regulatory changes [9] or military/performance athlete needs [10]. The studies from sleep medicine could offer great help to study thermal comfort in sleeping environments, but due to their different focus they usually cover extreme temperatures which rarely occur at typical sleeping environment and they also lack information on thermal comfort and covering insulation. There have been a few researches on sleeping thermal environment and thermal comfort of sleeping people. In this paper, the questions concerning the measurement and evaluation of human sleep quality, the correlation between thermal regulation system and sleep regulation, and the characteristics of night-time space cooling load etc., are answered. The evidences illustrating the effects of thermal parameters on human sleep quality are also provided, in an attempt to shed light on the thermal comfort requirements of sleeping people.

2. Ten questions concerning thermal environment and sleep quality

2.1. What are the characteristics of normal human sleep?

Answer: Normal human sleep is comprised of two states—rapid eye movement (REM) and non-REM (NREM) sleep—that alternate cyclically across a sleep episode [11,12].

NREM sleep includes a variably synchronous cortical electroencephalogram (EEG) (including sleep spindles, K-complexes, and

* Corresponding author.
E-mail address: zwlian@sjtu.edu.cn (Z. Lian).

http://dx.doi.org/10.1016/j.buildenv.2016.01.017

slow waves) associated with low muscle tonus and minimal psychological activity; the REM sleep EEG is desynchronized, muscles are atonic, and dreaming is typical. NREM sleep is conventionally subdivided into three stages (stages N1, N2, and N3) defined along one measurement axis, the EEG. The nightly pattern of sleep in adults sleeping on a regular schedule includes several reliable characteristics: Sleep begins in NREM and progresses through deeper NREM stages (stages N2 and N3) before the first episode of REM sleep occurs approximately 80–100 min later. The stage N3 sleep is characterized by slow wave activity (brain waves of frequency 0.5 Hz–2 Hz), thus is referred to as slow wave sleep (SWS) or deep sleep. NREM sleep and REM sleep alternate through the night, with an approximately 90-min cycle.

Generally, following statements can be made regarding sleep in the normal young adults who live on a conventional sleep-wake schedule and who do not have sleep complaints:

- SWS predominates in the first third of the night and is linked to the initiation of sleep and the length of time awake [13].
- REM sleep predominates in the last third of the night and is linked to the circadian rhythm of body temperature [14,15].
- Wakefulness in sleep usually accounts for less than 5% of the night.
- NREM sleep is usually 75%–80% of sleep.
- REM sleep is usually 20%–25% of sleep, occurring in four to six discrete episodes.

2.2. Why is thermal environment one of the most important factors that affect human sleep?

Answer: The thermoregulatory control center, known as the preoptic–anterior–hypothalamus (POAH), also regulates sleep. Even at the cellular level, there is an overlap in neurons sensitive to heat and neurons changing their firing pattern preceding and during sleep. These findings may explain the association between heat loss and preparedness to sleep observed in human sleep.

First described three-quarters of a century ago, the phenomenon that the onset of sleep is accompanied by vasodilation indicates the close linkage between thermoregulation and sleep [16]. Kräuchi et al. (1999) demonstrated that sleep onset latency correlated best with the amount of heat dissipation preceding sleep [17]. The parallel between sleep and heat loss is not surprising since the major brain region that drives heat loss (i.e., the POAH) is also of crucial importance in sleep regulation. von Economo proposed that sleep was regulated by opposing wake-promoting and sleep-promoting mechanisms localized in the hypothalamus [18]. The existence of such sleep-promoting mechanism in the POAH has been confirmed by later studies [19]. POAH contains populations of warm-sensitive and cold-sensitive neurons (WSNs and CSNs), which constitute 20–25% of neurons in these areas in vivo [20]. The activation of POAH WSNs (or deactivation of CSNs) is necessary and sufficient for control of NREM sleep [19,21]. The activity of WSNs is positively correlated with local or peripheral temperature. Mild to moderate ambient temperature elevation increases coincident sleep as well as subsequent sleep in rat [22,23]. Therefore, providing a thermal comfortable sleeping environment is important for sleep maintenance. Another important aspect to consider is that the thermoregulatory response during sleep differs depending on sleep stages [7]. Sensitivity to hot or cold stimulation is reduced during REM sleep compared to NREM sleep [24,25]. Sweat rate is lower in stages N1 and N2 of NREM than in slow-wave sleep (SWS), and the lowest in REM sleep [26], which consequently decreases evaporative heat dissipation and heat tolerance in REM sleep [7].

2.3. How to evaluate sleep quality in indoor environmental quality study?

Answer: Human sleep quality can be evaluated subjectively with questionnaires, and objectively using the recording of electrooculogram (EOG) for eye movements, electromyogram (EMG) for chin muscle tension, and electroencephalogram (EEG) for brain wave. The measurements of EMG, EOG, and EEG provide the basic information requisite for classifying sleep state and examining sleep processes.

The American Academy of Sleep Medicine (AASM) published a standardized manual for conducting these measurements, and made recommendations for recording, scoring, and summarizing the sleep stages [27]. The EEG, EOG, and EMG can be summarized according to such scoring criteria as sleep stages N1, N2, N3, and REM. The scoring criteria depend upon EEG bandwidth activity (delta, theta, alpha, and beta), EEG events (vertex sharp waves, sleep spindles, and K complexes), eye movement activity (slow and rapid eye movements), and the level of muscle tone. Stage N3 is characterized by high-amplitude slow-wave activity. Stage N2 contains sleep spindles and K complexes. Stage N1 has low-amplitude, mixed-frequency background, possibly slow eye movements, and vertex sharp waves. If rapid eye movements accompany the low-amplitude, mixed-frequency EEG, and skeletal muscle tone is low, rapid eye movement (REM) sleep is present [28].

The subjective assessments are usually divided into two types. One type is the examination of the sleep quality or habits in the previous days or months to determine the existence of sleep disturbances [29,30]. The other is daily evaluation, which is applied to assess the sleep quality of the previous night [31]. Although performing subjective evaluations is convenient, the perception of comfort of the subject is apt to be influenced by emotional or psychological stress. As to the sleeping thermal environment, the insulation level and style (covered or not) and the body posture (lying or seated) adopted when the subjective assessment is made would greatly affect thermoregulation and subjective perception. For example, when the body posture changes from upright to supine, skin blood flow is strongly promoted, and the distal and proximal skin temperatures increase [32], which then increase heat loss and decrease thermal sensation.

2.4. Whether the current thermal comfort standards and practices in air conditioning are applicable for sleeping people?

Answer: Many problems regarding thermal environment are found within a few field surveys in bedrooms, indicating that the current thermal comfort theories and standards, which are mainly concerned with people in waking state, are not applicable for sleeping people.

Nowadays, the use of air-conditioning is increasing remarkably, to maintain comfortable indoor thermal environments not only in workplaces at daytime, but also in sleeping spaces at night-time such as bedrooms of residences, guest rooms in hotels and wards in hospitals, at night-time. However, the current thermal comfort standards do not either differentiate the recommended design values for sleeping and waking people (EN 15251) [33], or exclude the application in sleeping or bed rest (ANSI/ASHRAE 55–2010) [34]. Sekhar and Goh (2011) measured the indoor air temperature of 12 air-conditioned bedrooms in summer and found that the mean temperature ranged from 22.5 °C to 25.5 °C [35]. Another field monitoring of 10 air-conditioned bedrooms in summer showed that the overnight mean indoor air temperature varied between 22.6 °C and 24.2 °C [36]. These measured results show that the air temperature of bedrooms was within the generally