Building and Environment 73 (2014) 24–31

Contents lists available at ScienceDirect

Building and Environment

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

Experimental study on thermal comfort of sleeping people at different air temperatures

Li Lan [a], Li Pan [a,b], Zhiwei Lian [a,*], Hongyuan Huang [c], Yanbing Lin [c]

[a] *Department of Architecture, School of Naval Architecture, Ocean & Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*
[b] *Shanghai Research Institute of Building Sciences, Shanghai 200032, China*
[c] *The Third Shanghai People's Hospital, Shanghai 201900, China*

ARTICLE INFO

Article history:
Received 24 September 2013
Received in revised form
29 November 2013
Accepted 30 November 2013

Keywords:
Thermal comfort
Air temperature
Sleep environment
Sleeping people
Sleep quality
Bedroom

ABSTRACT

Current thermal comfort theories and standards are mainly concerned with people in waking state. The effects of air temperature on sleep quality and thermal comfort of sleeping people were investigated in this study by experimenting on human subjects. Sleep quality was evaluated by subjective questionnaires performed in the morning as well as electroencephalogram (EEG) signals, which were continuously recorded during the all-night sleep period. Subjective assessments on thermal comfort were performed both before and after sleep. Analysis on EEG signals indicated that the subjects took longer time to fall asleep and experienced shorter period of slow wave sleep (SWS) when the room temperatures moderately deviated from neutral. Consistently, they reported poorer subjective sleep quality in such conditions. The returned subjective questionnaires on thermal comfort from subjects reflected that the thermal comfort temperature was higher in sleep compared with that in waking state. Their skin temperatures were increased with air temperature and fluctuated during the sleeping period. In view of the distinctive requirements from waking people, it makes sense to study the thermal comfort of sleeping people. The results also have practical implications on energy savings in bedrooms.

1. Introduction

1.1. Thermal environment and sleep quality

Sleep is essential for the body to recover from both physical and psychological fatigue suffered throughout the day and restore energy to maintain bodily functions [1]. Normal human sleep is comprised of two states – rapid eye movement (REM) and non-REM (NREM) sleep – that alternate cyclically across a sleep episode. 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 [2]. The stage N3 sleep is characterized by slow wave activity (brain waves of frequency 0.5 Hz–2 Hz), thus is referred as slow wave sleep (SWS) or deep sleep and is of vital importance to both body and mind. Studies with humans showed that poor sleep quality impaired cognitive performance in older adults [3], and impacted brain function related to reward processing, risk-taking, and cognition in adolescents [4]. Disturbed nocturnal sleep was also related to various adverse health problems, increasing the risk of cardiovascular disease and death [5].

Thermal environment could be one of the most important factors that affect human sleep. Very high or low air temperatures decreased SWS sleep, and increased the frequency and duration of wakefulness [6,7]. Moreover, thermoregulatory systems were shown to be strongly linked to the mechanisms regulating sleep [8–10]. The thermoregulatory control center, the preoptic – anterior – hypothalamus (POAH), also regulated sleep. It had been demonstrated in kangaroo and rat that peripheral thermal stimulation was capable of stimulating warm-sensitive neurons in the POAH, which in turn could promote sleep [11]. Therefore, providing a thermally comfortable sleeping environment is important for sleep maintenance and contributes positively to human health and their daytime activities.

1.2. Thermal comfort in sleep environment

Current thermal comfort theories and standards such as ANSI/ASHRAE 55-2010 [12] are primarily concerned with people in waking state although people spend a third of their lives sleeping. For office workers, the most occupied rooms are bedrooms when at home. Serving as a main technique to improve thermal comfort,

* Corresponding author. Tel.: +86 21 34204263.
E-mail address: zwlian@sjtu.edu.cn (Z. Lian).

0360-1323/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2013.11.024

bedroom air conditioner is becoming commonly accepted as being necessary and routine in many areas with hot summer. Our survey indicated that 90% of the 800 investigated families in Shanghai would use bedroom air conditioner in summer [13]. The survey in Hong Kong showed that 68% of the respondents would leave their air conditioners on throughout their sleep and only 6.1% used their air conditioners for less than 2 h during sleep in summer [14]. Similar results were found in Singapore [15]. Many problems regarding thermal environment were found within the few field surveys in bedrooms. Approximately 60% of the 554 respondents in Hong Kong experienced waking up during sleep because of thermal discomfort even with their air conditioners in operation [14]. A study in Korea showed that people were exposed to a variety of problems such as too low or high indoor temperatures when asleep [16]. These evidences suggest that the current thermal comfort standards and practices in air conditioning may not be applicable for sleeping people.

Over the last 20 years research on thermal comfort has undergone a dramatic intensification of activity. There are quantitative research on adaptive approach, air movement and personal comfort system but very limited research on thermal comfort of sleeping people. Lin and Deng (2008) measured the total insulation of the bedding systems commonly used in the subtropics and established a thermal comfort model determining thermally neutral conditions of sleep environment [17,18]. This thermal comfort model was developed based on Fanger's model by changing the insulation level and metabolic rate [18]. Pan et al. (2011) numerically studied the microclimate around a sleeping person in a space installed with a displacement ventilation system [19]. We proposed a bedside personalized ventilation (PV) system and found it could be used as a potential ventilation strategy to improve indoor air quality and thermal comfort in bedroom [20,21]. We also proposed the method for evaluation of sleep quality in thermal environment and observed significant effect of low indoor temperature on sleep quality of 8 human subjects in winter [22,23]. The studies from sleep medicine could offer great help to study thermal comfort in sleep environments, but they usually cover extreme temperatures and lack such information on thermal comfort as the covering insulation and thermal comfort perception etc. due to their different focus.

1.3. Objectives

To date there are few studies reporting the effects of moderate heat on human sleep quality although this could be a serious problem in areas suffering hot summer [14]. In a research context, evaluations of human subjects have superior contribution to knowledge and longer-lasting value to the research community than simulated evaluations coming out of a comfort model. In this study, physiological measurements and subjective assessments were made on human subjects in summer with the objectives to investigate the effects of moderate air temperature on sleep quality and to shed light on the thermal comfort requirements of sleeping people.

2. Methods

2.1. Subjects

Eighteen healthy Chinese students (9 males and 9 females; 20–25 years, mean ± STD: 23.3 ± 1.8 years; height: 158–181 cm, 171.8 ± 10.5 cm; weight: 46–75 kg, 58.1 ± 9.7 kg) were recruited from the University by advertisement. They were required to be nonsmokers, free of chronic diseases, asthma, allergy and hay fever, and were not taking any medications. All subjects had similar daily sleeping periods and did not suffer sleep disorder, which were verified by using the Pittsburgh Sleep Quality Index (PSQI) questionnaire during recruitment [24]. If the candidate had a PSQI global score >5, which is suggestive of a significant sleep disturbance, he/she was excluded. During the experiment, the subjects slept on a mattress bed in short-sleeved sleepwear and covered with thin blanket for the whole night; the insulation level of the covering materials including the sleepwear was estimated to be 1.64 clo [17]. They were asked to avoid caffeine, alcohol, smoking, and intense physical activity at least 12 h prior to each experimental session. The subjects were paid a salary for participating in the experiment at a fixed rate per night and did not receive any bonus. All protocols were approved by the university's ethics committee and conformed to the guidelines contained in the Declaration of Helsinki. Verbal and written informed consents were obtained from the subjects before they participated in the experiment.

2.2. Approach and facilities

The experiment was carried out in two identical and adjacent sleep chambers (4.5 m × 3.5 m × 3 m) of the university in the summer (Fig. 1). These two chambers were equipped with the same type of air conditioner that created the same thermal condition on each experimental night. The noise level in the sleeping chamber (occupants slept in the room) was 30 dB(A) at all conditions. Infrared camera was installed in the chamber to monitor the subjects.

The background temperature and humidity were measured with data logger at two positions, i.e., the middle of the bed head and bed end, both at a height of 0.4 m above the bed. The data logger (TR-72U, T&D corporation) has a built-in temperature sensor (range: 0–50 °C, accuracy: ±0.5 °C) and a humidity sensor (range: 10–95%, accuracy: ±5%). The air velocity was measured at the same positions with air flow sensor (UAS1100, Degree Controls Inc., range: 0.15–1.0 m/s, accuracy: ±5% of measured value). The temperature/humidity data loggers were calibrated in temperature humidity chamber. The airflow sensors were calibrated annually in wind tunnel.

2.3. Experimental design

Three air temperatures (23 °C, 26 °C, and 30 °C) expected to create cool, neutral and warm sleep environments were set in the chambers [18]. A within-subject design which asked each subject to sleep in his/her chamber alone for three successive nights under all

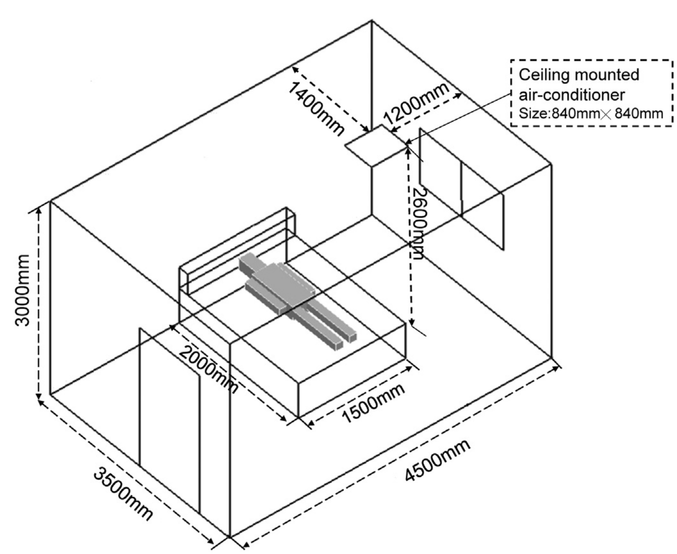

Fig. 1. Set-up of the experimental chamber.