Energy and Buildings 133 (2016) 843–852

Contents lists available at ScienceDirect

Energy and Buildings

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

Field study on the objective evaluation of sleep quality and sleeping thermal environment in summer

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ARTICLE INFO

Article history:
Received 16 March 2016
Received in revised form
22 September 2016
Accepted 8 October 2016
Available online 12 October 2016

Keywords:
Summer
Thermal environment
Sleep quality
SET
TSV
Thermal insulation

ABSTRACT

To validate the feasibility of Actiwatch 2 (AW2) to measure sleep quality in thermal comfort researches, five parameters drawn from AW2 and the subjective evaluation of sleep quality, sleep quality vote (SQV) were collected. Furthermore, to explore the effect of thermal environment and IAQ on sleep quality with AW2, the standard effective temperature (SET) was induced to evaluate the integrated effect of the sleeping thermal environment and CO2 was to indicate the freshness of air quality. Ambient temperature, relative humidity, mean radiant temperature, air velocity and CO_2 concentration were monitored in 6 bedroom of different type, including natural-ventilated rooms and air-conditioned rooms, during the hot season in Beijing for nearly one month. The occupant bedding system, posture habit and thermal sensation vote before sleep (BTSV) and after sleep (ATSV) of 3 female and 3 male subjects were recorded with questionnaire. The results showed that some of the sleep quality parameters measured by AW2 accorded with the subjective evaluation; Thermal environment had an effect on sleep quality according to the significant correlations between SET and the sleep quality parameters measured by AW2; The thermoneutral range of SET in sleeping condition was between 29.1–29.7 °C, based on which the thermal insulation of bedding system (I_{cl}) was recommended to be 0.96–1.08 clo.

1. Introduction

The previous field studies [24,20] of the occupant sleep quality used to investigate in a subjective way, while in sleep researches, sleep quality was usually objectively measured by EEG (electroencephalograph), which is a part of PSG (polysomnography) and can be used to analyze sleep stages [1,44,52] for a more precise outcome. However, either the wired electrodes taped to the skull or the wireless head belt that used to measure EEG, is likely to disturb sleep, and the accuracy of EEG/PSG can be easily affected by the surrounding electronic equipment. In the common protocol of thermal comfort studies, subjects are required to have no physical and mental diseases for the purpose that the effect of thermal conditions can be manifested among all the subjective and objective variables. Since the thermal conditions set in the sleeping thermal comfort research would not deviate from the neutral too much in case the subjects cannot fall asleep or cannot sleep after awakenings, the effects of the change in thermal conditions could easily be covered if their sleep quality is frequently disturbed by objective measurements. As we all know, even the same healthy person would have way different sleep quality in two consecutive nights. Therefore, the objective measurement of sleep quality used in the thermal comfort studies, should avoid interference as much as possible. Although actigraphy (ACTG) is less useful for documenting sleep-wake in persons who have long motionless periods of wakefulness (e.g. insomnia patients) or who have disorders that involve altered motility patterns (e.g., sleep apnea) [47], practice guidelines for actigraphy established by the Standards of Practice Committee of the American Academy of Sleep Medicine (AASM) [54] stated that actigraphy testing is reliable and valid for detecting sleep in normal, healthy populations. Abundant clinical studies showed that several important sleep quality parameters output by actigraphy had more than 80% agreement with the analysis result of PSG [6,3,25,48]. The sensors of ACTG has been currently developed as wireless and wearable watches that can be worn on the non-dominant wrist to monitor sleep, which makes ACTG very portable in the field studies.

There have been abundant studies on the effect of various thermal environment parameters on sleep quality, including ambient temperature [32,33,36,40], humidity [37–39], the total insulation of bedding system [28,30,31,41] and airflow, which can improve sleep quality in hot climates [56]. However, the integrated effect of thermal conditions of the sleeping environment on sleep qual-

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http://dx.doi.org/10.1016/j.enbuild.2016.10.007
0378-7788/© 2016 Published by Elsevier B.V.

Table 1
Detailed information about the subjects and their bedroom.

Subject	Gender	BMI	Room type	Thermal adjustments	Effective days of participation
1	Female	Medium	Single	Fan	21
2	Female	Low	Dorm	Fan	20
3	Female	Medium	Dorm	Air-conditioner	9
4	Male	Medium	Dorm	Air-conditioner	22
5	Male	High	Single	Fan	7
6	Male	Medium	Dorm	Fan	21

ity remains unknown. Considering the various occupant thermal adjustments people would resort to in the reality and only the air-conditioned bedroom was concerned in most existed field studies on sleeping thermal environment [5,16,49,4,29,26,27,50], a thermal index that can evaluate both steady and dynamic thermal environment is required. The standard effective temperature (SET), a single temperature index calculated through Gagge's two-nude model [13], is suggested to evaluate transient thermal environment with elevated airflow [2], and has been proved to have a well-linear relationship with thermal sensation vote(TSV) in the airflow condition when people were awake [18]. We may assume that SET can be induced to evaluate various thermal environment and correlate with thermal sensation vote (TSV) in sleeping condition as well. Other environmental factors, like the freshness of air, which can be determined by CO_2 concentration and indoor air quality (IAQ), affect sleep in some cases [10]. The cut-off point that CO_2 concentration would influence human sleep has not been determined yet [15] and there is no explicit conclusion on the effect of IAQ on sleep.

This paper reports on a field study of sleeping thermal environment and sleep quality in various built environments in summer. Firstly, the correlations between sleep quality vote(SQV) and the objective parameters of sleep quality was drawn to validate the feasibility of AW2; Secondly, the correlations between the standard effective temperature(SET), single thermal environmental parameters, CO2 concentration and the objective parameters of sleep quality was to see if SET could represent the thermal conditions; Thirdly, the range of the thermoneutral SET value and bedding systemin the sleeping condition was achieved through the regression equations between SET and TSVs.

2. Methods

2.1. Subjects and environmental conditions

The testing period started from the end of the July, the middle of the summer in Beijing. Pittsburgh sleep quality index (PSQI) [53], the time and place going to bed/getting up were investigated on 22 volunteers, to screen out the subjects who didn't have sleep disorders or change their bed for the last month, and shared a similar daily routing. Three male(age:27.3 ± 2.5, BMI:24.1 ± 1.7) and three female(age:22.3 ± 1.2, BMI:20.6 ± 2.0, the normal range of BMI:20 ∼ 25) subjects were selected out, for they met the following requirements: their PSQI were below 2(The total score is 5. The smaller the score the better the sleep quality is, and the score below 2 means the sleep quality is fair well); the sleeping time were all within 22:00 ∼ 8:00; each occupant gender covered different thermal adjustments, including the air-conditioned and natural-ventilated room, and different room type, including single rooms and rooms with several people occupied. The detailed information about the subjects and their bedroom were listed in Table 1. Dormitory rooms (Dorm), slept four students with a height of 3 m and a floor area of 17.1 m^2, and single rooms slept one student with a height of 3 m and a floor area of 8 m^2. They were monitored with environmental instruments, recording the ambient temperature, mean radiant temperature, relative humidity, air velocity and CO_2 concentration.

The bedding system settings, including posture habit, mat type, pajamas type, bedding and body coverage, and were chosen by the subjects through questionnaire. The partial insulation values of each item, I_{clu}, was referred to an unpublished study about measuring the Chinese traditional bedding system in lead sales with thermal manikin, in which the thermal insulation of air layer, mattress and the partial insulation values of various bedding items were achieved. The thickness and material of the pajamas in this study was similar to those measured with thermal manikin. The partial insulation of underwear panties and singlet was referred to ISO 9920 [19]. The total thermal insulation of the bedding system(subtract the thermal insulation of air layer), I_{cl}, can be estimated as the summation of the partial insulation (Table 2). Since the air velocity used to calculate the SET in this study was nightly averaged and therefore an estimated value, and the thermal insulation was also estimated by observation and a previous database, the effect of the direction of airflow on the convection heat transfer coefficient [9] was not taken into account in this study.

2.2. Measurement

2.2.1. Sleeping thermal environment

Ambient temperature, relative humidity and CO_2 concentration were measured by environmental self-recorders at an interval of 2 min; mean radiant temperature was by a black-bulb thermometer; the air velocity was by omnidirectional anemometers at an

Table 2
Components of bedding system and its estimated insulation.

Subject	Posture	Mat	Pajamas	Bedding	Body coverage (%)	I_{cl} (clo)
1	Side	Rattan	Panties(Underwear) and singlet	Towel blanket	67	0.77
I_{clu}(clo)	0.11	0.1	0.07	0.49		
2	Supine	None	Short sleeves and dress	Summer quilt	85.9	1.32
I_{clu}(clo)	0.22	0	0.17	0.93		
3	Supine	None	Short sleeves and dress	Summer quilt	67	1.08
I_{clu}(clo)	0.22	0	0.17	0.69		
4	Supine	None	Panties(Underwear)	Towel blanket	67	0.74
I_{clu}(clo)	0.22	0	0	0.49		
5	Side	Bamboo	Panties(Underwear)	Summer quilt	23.3	0.19
I_{clu}(clo)	0.11	0.05	0.03	0		
6	Supine	None	Short sleeves and panties	Summer quilt	67	1.17
I_{clu}(clo)	0.22	0	0.26	0.69		