https://doi.org/10.1016/j.buildenv.2020.107406

This is the Pre-Published Version.

Investigation of Thermal Comfort in Sleeping Environment and its Association with Sleep Quality

T. W. Tsang[a*], K. W. Mui[a], L. T. Wong[a]
[a]Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China
*Corresponding author
E-mail address: tszwun.tsang@connect.polyu.hk; Phone: +852 9813-8055;
Postal address: ZS817, 8/F, South Tower, Block Z, The Hong Kong Polytechnic University, Hung Hom, HKSAR

Abstract

Thermal environment can greatly influence one’s sleep quality, yet research into thermal satisfaction and sleep quality is lacking. This study investigates the thermal environment, thermal sensation, satisfaction and sleep quality of university students residing in dormitory in Hong Kong in winter. Based on subjective questionnaire and environmental measurement, it was found that under the same thermal condition, females selected a bedding system with higher total thermal resistance than males. Self-assessed overall sleep quality was associated with mid-sleep/ early awakenings, refreshment and duration of sleep, and sleep quality was largely influenced by thermal comfort and satisfaction. Thermally satisfied subjects and those with neutral thermal sensation had significantly better sleep quality. Thermal satisfaction and sleep quality toward hot and cold environments were also different. Existing sleeping thermal comfort models failed to predict accurately the thermal sensation in sleeping state, suggesting a need for the development of better prediction model for sleeping person.

Keywords

Sleeping thermal comfort; Thermal sensation; Thermal satisfaction; Sleep quality; Prediction model

1. Introduction

Human spend about one-third of time sleeping. Sleeping allows recovery of our body through various processes including replenishment of cerebral glycogen storage [1], cellular maintenance [2], etc. It is also vital for the removal of neurotoxins accumulated in the central nervous system during awake period [3]. Sleep disruption can result in short-term health problems like headache and pain [4], depression and anxiety [5]. Poor sleep quality also impairs cognitive ability and performance [6,7]. In long-term, chronic sleep deprivation increases risk of having cardiovascular diseases [8,9] and type-2 diabetes [10].

A lot of research has identified the relationship between thermoregulation and sleep, which is mainly facilitated by circadian rhythm of core temperature. Murphy and Campbell [11] found from an experiment that rapid decline in body core temperature enhanced sleep initiation and facilitated the entering of deeper stages of sleep. Kräuchi et al. [12] further confirmed the contribution of thermoregulation on sleep onset, concluded from the observation of a functional linkage between vasodilation of distal skin regions and subsequent skin temperature increase at the extremities and the ability to fall asleep.

Besides influencing the transition from wakefulness to early stage of non-rapid eye movement (NREM) sleep, thermal environment often affects the quality of sleep. Experimental study conducted in sleep laboratory with seven healthy men found decreases in slow wave sleep (SWS) and rapid eye movement (REM) sleep and increase in wakefulness under humid heat exposure at 35°C and 75% humidity [13]. Hot and humid environment in summer also impaired sleep efficiency by increasing the duration of mid-night awakenings [14]. Cold exposure at

21°C for five consecutive nights instead increased wakefulness and decreased stage 2 sleep without affecting other sleep stages [15]. Okamoto-Mizuno et al. [16] also confirmed the effect of cold exposure that it affected cardiac autonomic responses by altering heart rate variability (HRV) in stage 2 sleep and SWS, but did not affect sleep stage and subjective sensations, making an individual prone to adverse cardiac events during transition of sleep stage in winter [17]. It can be concluded that maintaining a comfortable thermal environment is crucial to good sleep quality and even health. Nonetheless, most of the thermal environmental guidelines or standards were formulated to satisfy awaken people instead of sleeping people, despite that studies have shown significant difference between thermal requirements of sleeping people and their awaken counterparts [18-20].

Thermal comfort studies in sleeping environment are limited, and those related to actual field data collection are lacking. The majority of sleeping thermal comfort studies investigated thermal comfort of sleeping people under controlled thermal conditions to determine the effect a particular factor on thermal comfort and/or sleep quality. Table 1 lists the details of selected thermal comfort studies related to sleep. Pan et al. [21] simulated winter environment (17°C, 20°C and 23°C) and investigated the sleep quality of 8 young adults based on subjective and physiological measurements. The study suggested that under thermal resistance of 3.12 clo, 23°C was the most satisfactory for sleeping. The sleep onset latency was also the shortest and the SWS was the longest at this temperature. Lan et al. [18] studied the effects of 3 pre-set air temperature (23°C, 26°C and 30°C) on sleep quality and thermal comfort of sleeping people and found that sleep quality was sensitive to change in air temperature. Under clothing resistance of 1.64 clo, neutral temperature at sleep (slightly above 26°C) was higher than that in awakening state (23°C), suggesting a difference in thermal sensation during sleep and wakefulness. On the contrary, a recent field study found that people have a lower neutral temperature during sleep than when awake [22]. While these studies collected subjective sleep quality data, the data were only evaluated together with indoor temperature instead of the thermal sensation and satisfaction.

To identify the thermal neutral environmental condition for sleeping people, Lin and Deng [23] developed a theoretical thermal comfort model for sleeping environment based on energy balance of human body and Fanger’s PMV model [24]. By introducing assumptions and modifications necessary for a sleeping person, for example metabolic rate, total thermal resistance by bedding system, etc., comfort equation for sleeping environment, hereby annotated as $\mathrm{PMV}_{\mathrm{sleep}}$, was derived, and comfort charts for sleeping environment were established by solving the comfort equation. The model suggests that total thermal insulation of bedding system significantly influences the thermal neutral temperature, with a linear relationship with slope of -0.189 clo/°C at 50% relative humidity. Lan et al. [25] later developed a two-part model, labelled as $\mathrm{PMV}_{\mathrm{2\text{-}part}}$, for evaluating thermal neutrality for sleeping people by considering the thermal balance of body parts in contact with the bed and not separately. The model’s ability to predict neutral temperature was validated using experiment results found in literature. Comparing to predictions made by $\mathrm{PMV}_{\mathrm{sleep}}$, $\mathrm{PMV}_{\mathrm{2\text{-}part}}$ gave estimations that agreed better with the experimental results with less than 5% deviations.

Sleep quality is affected by physiological, psychological and external stimulation [26]. Subjective thermal comfort survey is therefore more accurate and reliable in evaluating sleeping thermal environment than objective polysomnography assessment by considering the physiological adaptability and psychological satisfaction of the subjects [27]. In order to find out the linkage between subjective thermal sensations, thermal satisfaction and sleep quality, and to evaluate the usefulness of the two models in predicting the thermal sensation and thermal neutrality of sleeping people, this study collected actual sleeping thermal comfort field data from university students residing in dormitory in Hong Kong. Thermal environmental parameters and subjective thermal sensation, satisfaction and sleep quality data were gathered and evaluated. The association between thermal sensation, thermal satisfaction and sleep quality was also analyzed.

Nomenclature

Thermal comfort and sleep parameters

T_{out}	Outdoor temperature	V_a	Air velocity
RH_{out}	Outdoor relative humidity	A_c	Coverage percentage
T_a	Temperature	I_T	Clothing value
T_g	Global temperature	K	Constant
T_o	Operative temperature	NREM	Non-rapid eye movement sleep
$\bar{T}_r$	Mean radiant temperature	REM	Rapid eye movement sleep
RH	Relative humidity	SWS	Slow wave sleep

Thermal sensation model

PMV	Predicted mean vote by Fanger's model	PMV_{sleep}	Predicted mean vote by Lin and Deng's model
TSV	Thermal sensation vote	$PMV_{2\text{-}part}$	Predicted mean vote by Lan et al's model
L	Thermal load	p_a	Water vapor pressure in ambient air
Q_{skin}	Heat flow from skin	θ	Body area not in contact with the bed
Q_{res}	Heat flow by respiration	E_d	Heat loss by skin diffusion
C	Heat loss by convection	E_{cond}	heat loss by conduction through bed
R	Heat loss by radiation	λ	Heat of vaporization of water
E_{sk}	Total evaporative heat loss from skin	D_m	Permeance coefficient of the skin
C_{res}	Sensible heat loss by respiration	$p_{sk,a}$	Water vapor pressure in saturated air at $\bar{t}_{sk,a}$
E_{res}	Evaporative heat loss by respiration	$\bar{t}_{sk,a}$	Mean skin temperature of body not in contact with bed
h_c	Heat transfer coefficient by convection	k	Thermal conductivity of bed
h_r	Heat transfer coefficient by radiation	$p_{sk,b}$	Water vapor pressure in saturated air at $\bar{t}_{sk,b}$
$\bar{t}_{sk}$	Skin temperature	$\bar{t}_{sk,b}$	Mean skin temperature of body in contact with bed
R_{cl}	Clothing thermal resistance	T_b	Surface temperature of bed
f_{cl}	Clothing area factor	d	Thickness of bed in meter
R_t	Total thermal resistance	$\dot{m}_{res}$	Pulmonary ventilation rate
M	Metabolic rate	t_{ex}	Temperature of expired air
α	Sensitivity coefficient	W_{ex}	Humidity ratio in expired air
w	Skin wittedness	W_a	Humidity ratio in inspired air
$p_{sk,s}$	Water vapor pressure in saturated air at $\bar{t}_{sk}$	A_D	Body surface area

Statistical analysis

r_{pb}	Point-biserial correlation coefficient	S_n	Standard deviation of X
X	Binary variable	n_1	Sample size for X = 1
Y	Continuous variable	n_0	Sample size for X = 0
M_1	Mean value of Y for X = 1	n/N	Sample size
M_0	Mean value of Y for X = 0	SD	Standard deviation of data

Table 1. Experimental/field studies of thermal comfort in sleeping environment

Ref	Aim	Location	Sample size	Evaluation method	Highlighted results
[18]	Thermal comfort of sleeping people at different air temperature	Sleep chamber	18 female: 9 male: 9 mean age: 23.3±1.8	Objective: Electroencephalogram (EEG), skin temperature Subjective: ASHRAE 7-point thermal sensation scale, 5-point thermal comfort vote , subjective sleep quality questionnaire	Sleep quality was sensitive to air temperature and thermal neutral temperature was higher in sleep compare with waking state
[21]	Effects of different ambient temperatures on sleep quality	Sleep chamber	8 female: 8 male: 8 mean age: 21.0±2	Objective: mean skin temperature, electroencephalogram (EEG) Subjective: ASHRAE 7-point thermal sensation scale, sleep quality questionnaire	T_a = 23°C achieved the highest score for freshness after awakening, ease of falling asleep, ease of awakening, freshness after waking up and sleep satisfaction. Subjective and objective sleep quality was the best at 23°C and worst at 17°C.
[22]	Field study of indoor environmental quality and sleep quality in sleeping environment	Student dormitories	24 female:16 male: 8 mean age: 19.7±1.2	Objective: environmental parameters Subjective: Pittsburgh Sleep Quality Index (PSQI), ASHRAE 7-point thermal sensation scale, subjective evaluation of indoor environmental quality	Ambient temperature and noise were the most important sleep factor, with most satisfying T_o = 24.2°C. Subjects had lower neutral temperature and broader accepted temperature range during sleep.
[27]	Effects of sleep environment on sleep quality and local skin temperature	Sleep laboratory	12 female: 6 male: 6 mean age: 24±1	Objective: mean skin temperature, bedding temperature Subjective: ASHRAE 7-point thermal sensation scale, sleep quality questionnaire	Micro-environment in bed with cover had a greater effect on thermal comfort than ambient climate. Subjects preferred a slightly cool sleeping thermal environment. Sleep quality is highest at T_o = 15.8°C.
[40]	Gender difference in sleep comfort at various temperature	Sleep chamber	8 female: 8 male: 8 mean age: 21.0±2	Objective: mean skin temperature, electroencephalogram (EEG) Subjective: ASHRAE 7-point thermal sensation scale, sleep quality questionnaire	Males preferred cooler sleeping environment than females, which could be the physiological differences. Females were more sensitive to cool environment, males on the other hand were less tolerable to heat.
[52]	Effects of bed climate on sleeping thermal comfort	Climate controlled chamber	12 mean age: 23.4±1.4	Objective: skin temperature, mean bedding temperature, ambient temperature, relative humidity Subjective: ASHRAE 7-point thermal sensation scale, 5-point thermal comfort vote	Bed climate played an important role in thermal comfort than ambient environment. Much lower T_a was accepted with proper quilts.
[61]	Sleeping thermal environment for human comfort and gender-specific difference	Climate chamber	12 female: 6 male: 6 mean age: 23.5±0.7	Objective: ambient thermal condition, skin temperature Subjective: ASHRAE 7-point thermal sensation scale, 5-point thermal comfort vote, 7-point thermal preference scale, subjective sleep quality questionnaire	Mean bed temperature for thermal comfort was 30.2-31°C, with a relatively low T_a due to high clothing insulation provided by bedding system. Male had a 1.5°C lower neutral temperature than female.

[70]	Effect of programmed air temperature changes on sleep quality	Climate controlled chamber	12 female: 6 male: 6 mean age: 23	Objective: electroencephalogram (EEG), electrooculogram (EOG), electromyogram (EMG), skin temperature, neurobehavioral performance test Subjective: ASHRAE 7-point thermal sensation, subjective sleep quality assessment	No significant difference in thermal comfort or sleep quality among various temperature change scenario. Fall-rise condition (i.e. slight decrease of T_a at later sleep stage) could prepare the body for better wake up.
[71]	Effect of temperature of human-mattress interface on thermal comfort	Humidity-controlled room	29 female: 12 male: 17 age: 23-40	Objective: skin temperature Subjective: ASHRAE 7-point thermal sensation scale, comfort questionnaire	Total increase of temperature at the interface was associated with a reduction in comfort.

2. Methodology

2.1. Field measurement

Field measurements were conducted in a university dormitory in Hong Kong during winter time from November 2018 to March 2019. To assess the thermal environment, indoor environmental parameters including indoor air temperature (T_a), global temperature (T_g), relative humidity (RH), air velocity (V_a) were measured by Lutron Heat Index WBGT Meter (WBGT-2010SD) and TSI Air Velocity Transducer (TSI-8475) throughout the night with a logging interval of 1 min, started from before the subject sleep and ended after they woke up. Devices were place near the head area of the subject. In thermal comfort study, convective and radiative heat loss from skin shall be expressed in terms of operative temperature (T_o) and mean radiant temperature ($\bar{T}_r$), which can be computed with Equations (1)–(3) below, where ε and D are the emissivity and diameter of the globe, h_c is the convective heat transfer coefficient.

$$\bar{T}_r = \left[\left(T_g + 273\right)^4 + \frac{1.1\times10^8\times{V_a}^{0.6}}{\varepsilon\times D^{0.4}}\left(T_g - T_a\right)\right]^{0.25} - 273 \qquad (1)$$

$$T_o = \frac{4.7\bar{T}_r + h_c T_a}{4.7 + h_c} \qquad (2)$$

$$h_c = \begin{cases} 5.1, & 0 < V_a \leq 0.15 \\ 2.7 + 8.7{V_a}^{0.67}, & 0.15 < V_a < 1.5 \end{cases} \qquad (3)$$

In addition to collecting thermal environmental data, interviewees were required to report their time of sleep and awakening. With reference to thermal insulation by bedding system commonly used in Hong Kong suggested in Lin and Deng [28], students were asked to select the combination of bedding cover (i.e. blanket or quilt of various thicknesses) and sleepwear (i.e. naked, half or full-slip) they adopted during sleep and the percentage coverage of body surface area by bedding and bed (A_c). Since the dorm provided the same type conventional mattress for everyone, the total clothing insulation values (I_T) provided by bedding system and clothing can be estimated according to Lin and Deng [28], and the total thermal resistance can be determined by Equation (4), where K is a unit constant of 6.45 clo W/m^2°C.

$$I_T = KR_t \qquad (4)$$

It is noteworthy that as though other environmental factors have been found to influence sleep quality, for example noise [29], the purpose of this study is to investigate the effect of thermal conditions on sleep quality, therefore other factors were not considered. As a matter of fact, control experiment was not intended in this study. The prime interest is to evaluate the sleeping thermal environments, and the relationship between sleeping thermal sensation, thermal satisfaction and sleep quality. Students were free to select their most comfortable environmental conditions to conduct this study.

2.2. Subjective questionnaire

10 university students (6 male; 4 female; 18–25 years old) residing in double rooms and triple rooms of 9-person suite, shown in Figure 1, were interviewed. With reference to Table 1 above, comparable number of subjects were considered in most of the sleeping thermal comfort studies established previously. A repeated measurement design was adopted to allow fewer subjects for more efficient data collection with less variance. Students were asked to take part in the field measurement more than 2 times, depending on their availability. All of them were non-smoker and non-alcoholic, and were also free of chronic diseases, diagnosed sleeping disorders

and any long-term medication. They were required to avoid intense physical activities like exercising, consumption of alcohol and caffeine at least 8 hours prior to the test period to minimize the influence of daytime activities on sleep quality.

Interviewees were asked to complete a questionnaire, shown in Table 2, immediately after they woke up. The questionnaire includes subjective thermal sensation and satisfaction assessment evaluated using ASHRAE seven-point thermal sensation scale and a dichotomous yes/ no question respectively [30], and subjective assessment of sleep quality based on Pittsburgh Sleep Quality Index (PSQI). PSQI is a self-report subjective measure of quality of sleep and sleep patterns by evaluating seven domains including quality, latency, duration, habitual sleep efficiency, disturbances, use of sleep medication, and daytime dysfunction over the past month [31]. To serve the purpose of this study, the questionnaire was modified to collect data about sleep quality, latency and disturbance only. Questions relating to use of sleep medication, habitual sleep efficiency and daytime dysfunction were not included as these items do not apply to the research scope. Instead, subjective questionnaire employed by Lan et al. [18] was considered as their study also investigated last-night sleep quality. Questions regarding ease of awakening and sufficient sleep were added into the modified PSQI questionnaire. Sleep quality was therefore assessed by a total of 12 yes/ no questions and an overall sleep quality scale. The global PSQI score was calculated by adding together the score of 13 individual questions. A higher score suggested a better sleep quality.

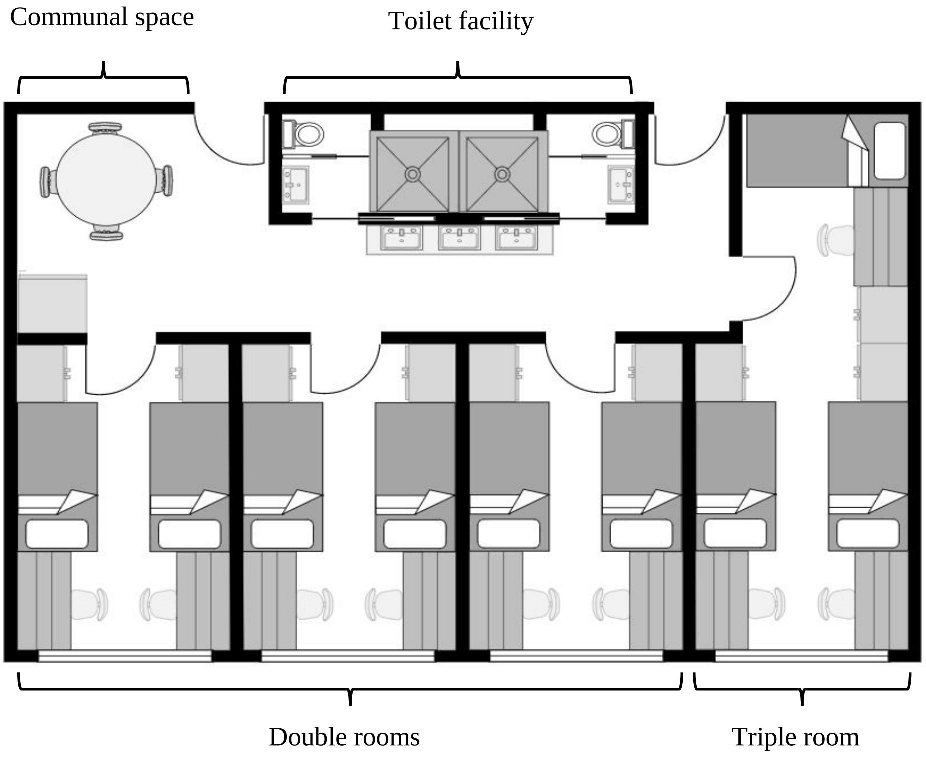

Figure 1. Layout of a typical 9-person suite with details of double rooms, triple rooms, communal space and toilet facility.

Table 2. Subjective questionnaire for thermal sensation, thermal satisfaction and sleep quality.

Thermal sensation vote						
What was your thermal sensation during sleep?						
–3 Cold	–2 Cool	–1 Slightly cool	0 Neutral	+1 Slightly warm	+2 Warm	+3 Hot

Thermal satisfaction					
Were you satisfied with your thermal environment during sleep?					
	Satisfied (1)		Dissatisfied (0)		
Sleep quality					
1	I could not get to sleep within 30 minutes last night.	Yes (0)		No (1)	
2	I woke up in midnight and/ or early morning.	Yes (0)		No (1)	
3	I had to get up in the middle of night to use the bathroom.	Yes (0)		No (1)	
4	I had trouble breathing last night.	Yes (0)		No (1)	
5	I coughed and/ or snored loudly last night.	Yes (0)		No (1)	
6	I felt too cold last night.	Yes (0)		No (1)	
7	I felt too hot last night.	Yes (0)		No (1)	
8	I had bad dreams last night.	Yes (0)		No (1)	
9	I had pain last night.	Yes (0)		No (1)	
10	It was easy to wake up this morning.	Yes (1)		No (0)	
11	I felt refreshed right after waking up.	Yes (1)		No (0)	
12	I had enough sleep.	Yes (1)		No (0)	
13	Overall sleep quality	Very good (3)	Fairly good (2)	Fairly bad (1)	Very bad (0)

2.3. Sleeping thermal comfort model

Thermal load (L) can be expressed by Equation (5)–(6), where Q_{skin} is the heat flow from skin, Q_{res} is the heat flow by respiration, where C and R are the convection and radiation heat loss from outer surface of a clothed body, E_{sk} is the total evaporative heat loss from skin, C_{res} and E_{res} are sensible and evaporative heat loss by respiration.

$$L = M - Q_{skin} - Q_{res} \tag{5}$$

$$L = M - (C + R + E_{sk}) - (C_{res} + E_{res}) \tag{6}$$

Sensible heat loss from skin is achieved by convection and radiation through clothing, which can be expressed by Equation (7), where h_c and h_r are the respective heat transfer coefficient, $\bar{t}_{sk}$ is the skin temperature, R_{cl} is clothing thermal resistance, f_{cl} is the clothing area factor.

$$C + R = \frac{\bar{t}_{sk} - T_o}{R_{cl} + 1/f_{cl}(h_r + h_c)} \tag{7}$$

For sleeping person in a bedding system, clothing area factor and clothing thermal resistance cannot be determined. Instead, a total thermal resistance (R_t) consisted of the entire bedding system, sleepwear and surrounding air is adopted such that Equation (7) is simplified [23]:

$$C + R = \frac{\bar{t}_{sk} - T_o}{R_t} \tag{8}$$

To evaluate the thermal comfort sensation and satisfaction, Fanger proposed a Predicted Mean Vote (PMV) index heat balance equation and experimental results collected from climate chamber study, shown in Equation (9) where M is the metabolic rate and L is the thermal load on the body defined by the difference between body heat production and heat loss to the surrounding, α is a sensitivity coefficient obtained in the controlled experiment with human subjects conducting activities with various metabolic rates [24].

$$PMV = (0.303e^{-0.036M} + 0.28)L = \alpha L \tag{9}$$

In Fanger's PMV expression, a seated person is believed to have a metabolic rate of 1 met (58.15 Wm^{-2}). For a sleeping person, metabolic rate drops to 0.7 met (40 Wm^{-2}). Based on the belief that the α value can be applied to activity with lower metabolic rate, and with the assumption of no regulatory sweating during sleep (i.e. skin wittedness (w = 0.06)) [32], $\bar{t}_{sk}$ = 34.6°C, water vapor pressure in saturated air at $\bar{t}_{sk}$ ($p_{sk,s}$ = 5.52 kPa), estimation of $C_{res} = 0.0014M(34 – T_a)$ and $E_{res} = 0.0173M(5.87 – p_a)$ [33], Lin and Deng [23] developed a thermal comfort model for sleeping environment expressed in Equation (10), with p_a be the water vapor pressure in ambient air.

$$PMV_{sleep} = 0.0998\left\{40 - \frac{1}{R_t}[(34.6 - T_o) + 0.3762(5.52 - p_a)]\right\} - 0.0998[0.056(34 - T_a) + 0.692(5.87 - p_a)] \qquad (10)$$

Lan et al. [25] developed a two-part model for evaluating the thermal neutrality for sleeping Chinese individuals. In the model, the thermal balance of body parts in contact with the bed and the rest were considered separately. Equation (6) is therefore expressed with a coefficient of (1 – θ), which describes the body area that are not in contact with the bed. θ was estimated to be 0.39 when body is in supine position [34,35]. Equation (5) is expressed as Equation (11) below, where E_d and E_{cond} are the heat loss by skin diffusion and by conduction through bed, estimated by Equation (12)–(13) respectively, with λ be the heat of vaporization of water (2418 kJ/kg at 34°C), D_m the permeance coefficient of the skin (1.27×10^{-6} g/(sm^2Pa)), $p_{sk,a}$ the water vapor pressure in saturated air at $\bar{t}_{sk,a}$, the mean skin temperature of body not in contact with bed (34.6°C), k the thermal conductivity of bed (0.048 W/m^2K), $p_{sk,b}$ the water vapor pressure in saturated air at $\bar{t}_{sk,b}$, mean skin temperature of body in contact with bed (35.4°C), T_b the surface temperature of bed (assume to be equal to T_a), and d the thickness of bed in meter.

$$L = M - [(1 - \theta)(C + R) + E_d + E_{cond}] - (C_{res} + E_{res}) \qquad (11)$$

$$E_d = \lambda D_m \times (1 - 0.8\theta)(p_{sk,a} - p_a) \qquad (12)$$

$$E_{cond} = k\theta\frac{\bar{t}_{sk,b} - T_b}{d} \qquad (13)$$

Instead of estimating the C_{res} and E_{res} according to the ASHRAE handbook, Lan et al. [25] expressed the sensible and evaporative heat loss by respiration by Equation (14)–(15), where $\dot{m}_{res}$ is the pulmonary ventilation rate of sleeping people (0.128 g/s) [36], t_{ex} is the temperature of expired air (34°C), $W_{ex} – W_a = 29 – 0.0049p_a$ is the difference in humidity ratio between expired air and inspired air expressed in [37], A_D is the body surface area of Chinese people estimated by Zhao et al. [34] and Zhao et al. [35].

$$C_{res} = \frac{\dot{m}_{res} c_p (t_{ex} - T_a)}{A_D} \qquad (14)$$

$$E_{res} = \frac{\dot{m}_{res} \lambda (W_{ex} - W_a)}{A_D} \qquad (15)$$

Based on the Equation (11)–(15), PMV predicted by 2-part model can therefore be expressed as:

$$PMV_{2-part} = 0.0998\left\{40 - \frac{13.41 - 1.519p_a - 0.13T_a}{A_D} - \left[1.875 \times (5.52 - p_a) + \frac{0.61\times(34.6 - T_o)}{R_t} + 0.0187 \times \frac{35.4 - T_a}{d}\right]\right\} \qquad (16)$$

2.4. Statistical analysis

Associations between sleep problems and sleep quality, thermal sensation, thermal satisfaction and sleep quality were identified using point-biserial correlation. Point-biserial correlation analysis measures the strength of association between a dichotomous (or binary) variable – sleep problem, neutral thermal sensation vote (TSV) and thermal satisfaction, and a continuous variable – overall sleep quality and global PSQI score. Point-biserial correlation analysis would result in a correlation coefficient (r_{pb}) ranging from -1 to +1, with -1 indicates a perfect negative association, vice versa, and 0 suggests no association. Equation (17) shows how the point-biserial correlation coefficient is computed, given that X = {0,1} and Y = {y_1, …, y_n}, M_1 being the mean value on the continuous variable Y for all data points in X = 1, and M_0 the mean value on Y for all data points in X = 0, n_1 is the sample size for X = 1, n_0 is the sample size for X = 0, n is the total sample size and S_n is the standard deviation of X.

$$r_{pb} = \frac{(M_1 - M_0)\sqrt{n_1 n_0}}{nS_n} \tag{17}$$

To determine whether r_{pb} is statistically significantly different from zero, two-tailed *t*-test at 95% confident interval was adopted.

3. Results

3.1. Measurement results

A total of 38 sets of environmental data and questionnaires were collected in the study. Since the survey was conducted in winter, air conditionings and fans were not used. Rooms were ventilated naturally with open window. Interviewees had an average of 7.8 hours (SD = 1.2) of sleep, which fell within the recommended sleep duration by National Sleep Foundation, American Academy of Sleep Medicine and Sleep Research Society in the United State. Measurement data taken between 30 minutes after the subject was on bed and 30 minutes before waking up were adopted in data analysis to ensure adaptation to thermal environment. Table 3 shows the measurement data of female and male students. Figure 2 shows the clothing value selected by male and female students at different operative temperature. The size of the bubble indicates the coverage percentage. There were well-fit trends of decreasing clothing value (R^2 = 0.88) and coverage percentage (R^2 = 0.75) with increasing operative temperature for male students. No such trends were observed for female students.

Table 3. Measurement data of female and male students.

		Female (N = 9)		Male (N = 29)		*p*-value,
	unit	Mean	SD	Mean	SD	*t*-test
Outdoor						
Temperature (T_{out})	°C	18.9	2.1	19.7	2.1	0.41
Relative humidity (RH_{out})	%	85.1	8.2	83.1	10.4	0.58
Indoor						
Temperature (T_a)	°C	22.3	1.5	23.6	1.9	0.06
Global temperature (T_g)	°C	22.1	1.6	23.4	1.9	0.07
Mean radiant temperature ($\bar{T}_r$)	°C	22.1	1.6	23.4	1.9	0.07
Operative temperature (T_o)	°C	22.2	1.6	23.5	1.9	0.07
Relative humidity (RH)	%	78.2	7.1	72.1	9.8	0.06
Air velocity (V_a)	ms^{-1}	0.0004	0.00026	0.00043	0.00022	0.74
Bedding system						
Clothing value (I_T)	clo	4.1	0.6	3.4	1.0	<0.05
Coverage percentage (A_c)	%	90.4	8.5	80.3	16.4	<0.05

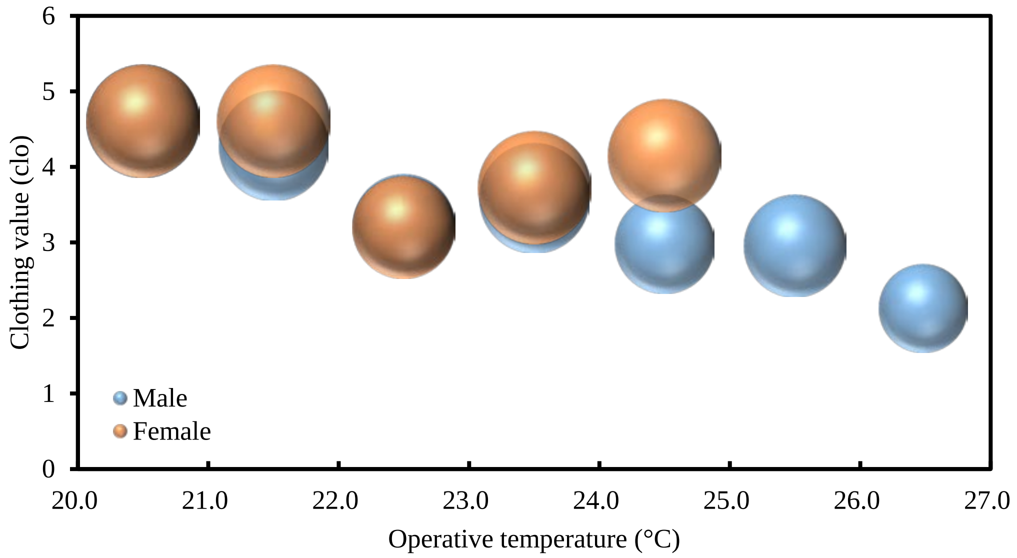

Figure 2. Clothing value and coverage percentage selected by students at different operative temperature.

3.2. Subjective sensation

Thermal sensations were evaluated by TSV, thermal satisfaction and the two above-mentioned sleeping thermal comfort models. Table 4 shows the measurement data of thermally satisfied and dissatisfied groups of students. Results suggested that thermal satisfactions were sensitive to operative temperature. Significant difference were found in TSV and $PMV_{2\text{-part}}$ of the two groups but not PMV_{sleep}. Both sleeping thermal comfort models overestimated the thermal sensations of students during sleep, surprisingly with a negative correlation given by Equation (18)–(19). Figure 3(a) demonstrates the correlation between TSV, PMV_{sleep} and $PMV_{2\text{-part}}$; 3(b) shows the relationship between TSV/PMVs and selected total clothing value.

$$TSV = -7.2PMV_{2-part} + 9.5, \quad R^2 = 0.60 \tag{18}$$

$$TSV = -4.2PMV_{sleep} + 4.7, \quad R^2 = 0.75 \tag{19}$$

Table 4. Thermal sensation result by satisfied and dissatisfied groups.

	Satisfied (N = 23)		Dissatisfied (N = 15)		*p*-value,
	Mean	SD	Mean	SD	*t*-test
Indoor					
Operative temperature (T_o)	23.9	1.7	22.2	1.7	<0.05
Air velocity (V_a)	0.0004	0.00028	0.0005	0.00012	0.39
Bedding system					
Clothing value (I_T)	3.5	1.0	3.7	0.9	0.72
Coverage percentage (A_c)	82.9	14.9	82.4	16.3	0.92
Thermal Vote					
$\lvert TSV \rvert$	0.4	0.6	1.5	0.5	<0.05
$\lvert PMV_{sleep} \rvert$	1.4	1.5	1.1	0.5	0.17
$\lvert PMV_{2\text{-part}} \rvert$	1.5	0.2	1.3	0.3	<0.05

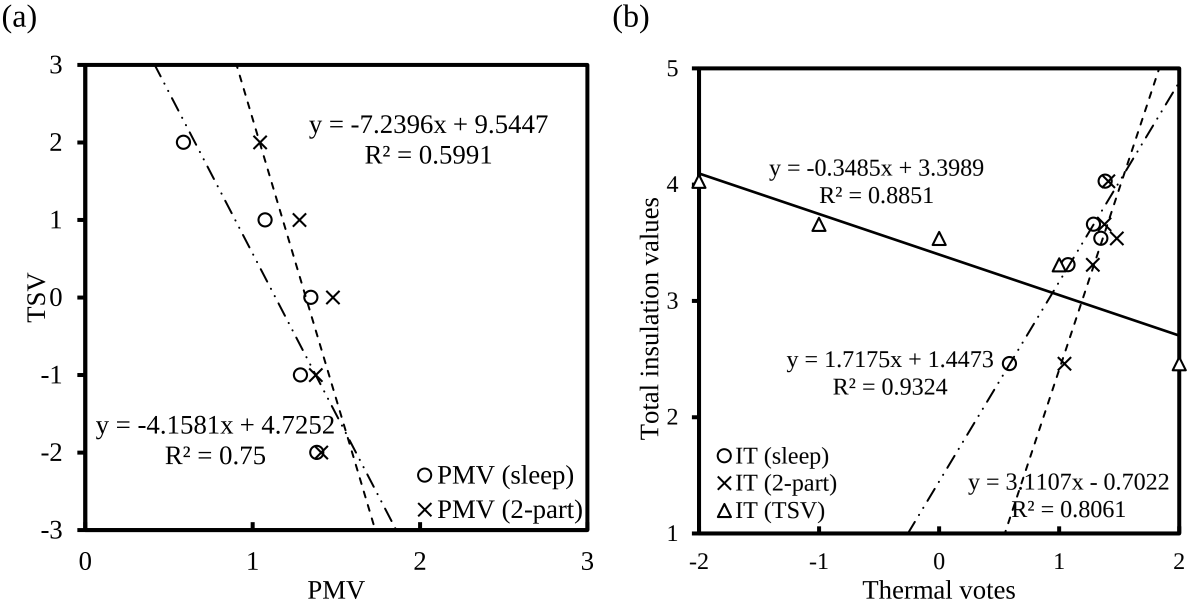

Figure 3. (a) Correlation between TSV and PMVs by selected sleeping thermal comfort models; (b) Correlation between TSV/PMVs and selected total clothing value.

Figure 4(a) exhibits a positive correlation between TSV and operative temperature, with R^2 = 0.73, suggesting subjective thermal sensation was sensitive to the change in ambient thermal condition. In order to determine the preferred neutral temperature for sleeping young adults, based on the method suggested by Wong et al. [38], interviewees were divided into Group –: voted for a cool TSV (prefer warmer; N = 19) and Group +: voted for a warm side TSV (prefer cooler; N = 5). Figure 4(b) shows the percentiles ϕ of the two groups at various operative temperatures approximated by normal distributions. From the result, the neutral temperature T_n for sleeping university students was determined as 23.05°C, where the two lines intercept with each other, i.e. $\phi_{-}|_{T_o} = \phi_{+}|_{T_o}$. Alternatively, neutral temperature can be computed simply by taking the average of operative temperatures which the interviewees had a neutral thermal sensation (i.e. TSV = 0), which was 23.81°C with average I_T = 3.54 clo.

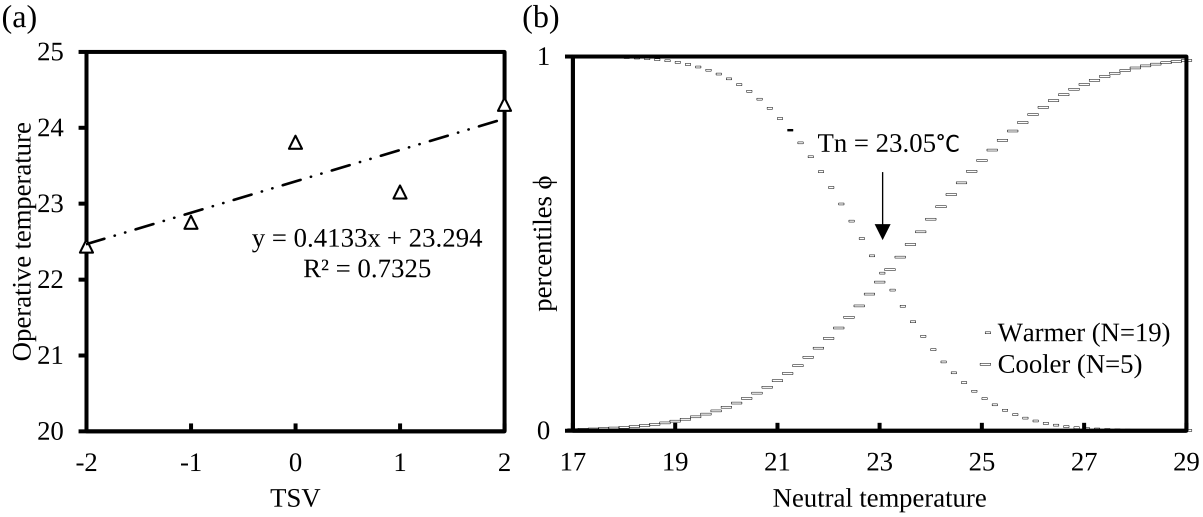

Figure 4(a). Correlation between TSV and operative temperature; (b) Neutral temperature of university students with average I_T = 3.58 clo and M = 0.7 met.

3.3. General sleep quality

Sleep quality of students were evaluated by a modified PSQI questionnaire consisted of 13 questions and an aggregate global PSQI score. Question 4–9 recorded with a less than 5 “Yes (0)” count. Majority of the interviewees had problems with sleep latency (Q1: 31.6%), mid-sleep/ early awakenings (Q2: 52.6%), difficulty waking up (Q10: 42.1%) and tiredness after waking up (Q11: 36.8%). It is noteworthy that the students had an average of 7.8 hours of sleep during the measurement, which were deemed adequate for this age range. Sleep problems identified by interviewees could indicate poor sleep quality caused by environmental factors. Associations between individual question with meaningful sample size (i.e. both Yes and No count ≥5) (Q1–3, 10–12) and self-assessed overall sleep quality (Q13) were evaluated using point-biserial correlation. Table 5 exhibits the point-biserial correlation coefficient (r_{pb}) which measures the strength of association and *p*-value. It was concluded that self-assessed overall sleep quality was positivity correlated with mid-sleep/ early awakenings, refreshment and duration of sleep.

Table 5. Association between individual sleep aspects and overall sleep quality.

	Q1	Q2	Q3	Q10	Q11	Q12
Sleep problem	sleep latency	mid-sleep/ early awakenings		ease for waking up	refreshment	duration
r_{pb}	0.24	0.46	0.36	0.3	0.58	0.39
p-value, *t*-test	0.14	<0.005	<0.05	0.06	<0.005	<0.05

3.4. Sleep quality and thermal comfort

To find out the effect of thermal environment on sleep quality, data were categorized into groups for analysis. The first comparison was done between sleep quality data collected from students with neutral TSV (TSV = 0) and those without (TSV = –2/–1/+1/+2), and the second was between sleep quality data collected from interviewees who were thermally satisfied with the environment and those who were dissatisfied. Table 6 describes the data in each group. Results suggested that when people had a neutral TSV, they tended to be thermally satisfied (= 0) than those who voted the rest. Self-assessed overall sleep quality and global PSQI score were also significantly higher if they had a neutral TSV. It was also found that thermally satisfied group had significantly higher self-assessed overall sleep quality and global PSQI score. Figure 5 shows the boxplots of overall sleep quality and global PSQI score of non-neutral/neutral TSV group and dissatisfied/satisfied groups. Association between thermal sensation/satisfaction and overall sleep quality/global PSQI score were indicated by point-biserial correlation coefficient shown in the figure.

Interestingly, students voted for a cool TSV (TSV = –2/–1) had slightly higher average global PSQI score and thermal satisfaction than those who voted for a warm TSV (TSV = +1/+2) (*p*-value, *t*-test = 0.05). Figure 6 exhibits the relationship between TSV, average global PSQI score and thermal satisfaction.

Table 6. Thermal sensation, thermal satisfaction and sleep quality.

	TSV = 0 (N = 14)		TSV = –2/–1/+1/+2 (N = 24)		*p*-value, *t*-test	Satisfied (N = 23)		Dissatisfied (N = 15)		*p*-value, *t*-test
	Mean	SD	Mean	SD		Mean	SD	Mean	SD	
Thermal satisfaction	1	0	0.38	0.48	<0.001	NA				
Overall sleep quality	2.43	0.49	1.71	0.54	<0.001	2.30	0.46	1.47	0.50	<0.001
Global PSQI score	13.86	1.25	10.46	1.58	<0.001	13.09	1.47	9.6	1.25	<0.001

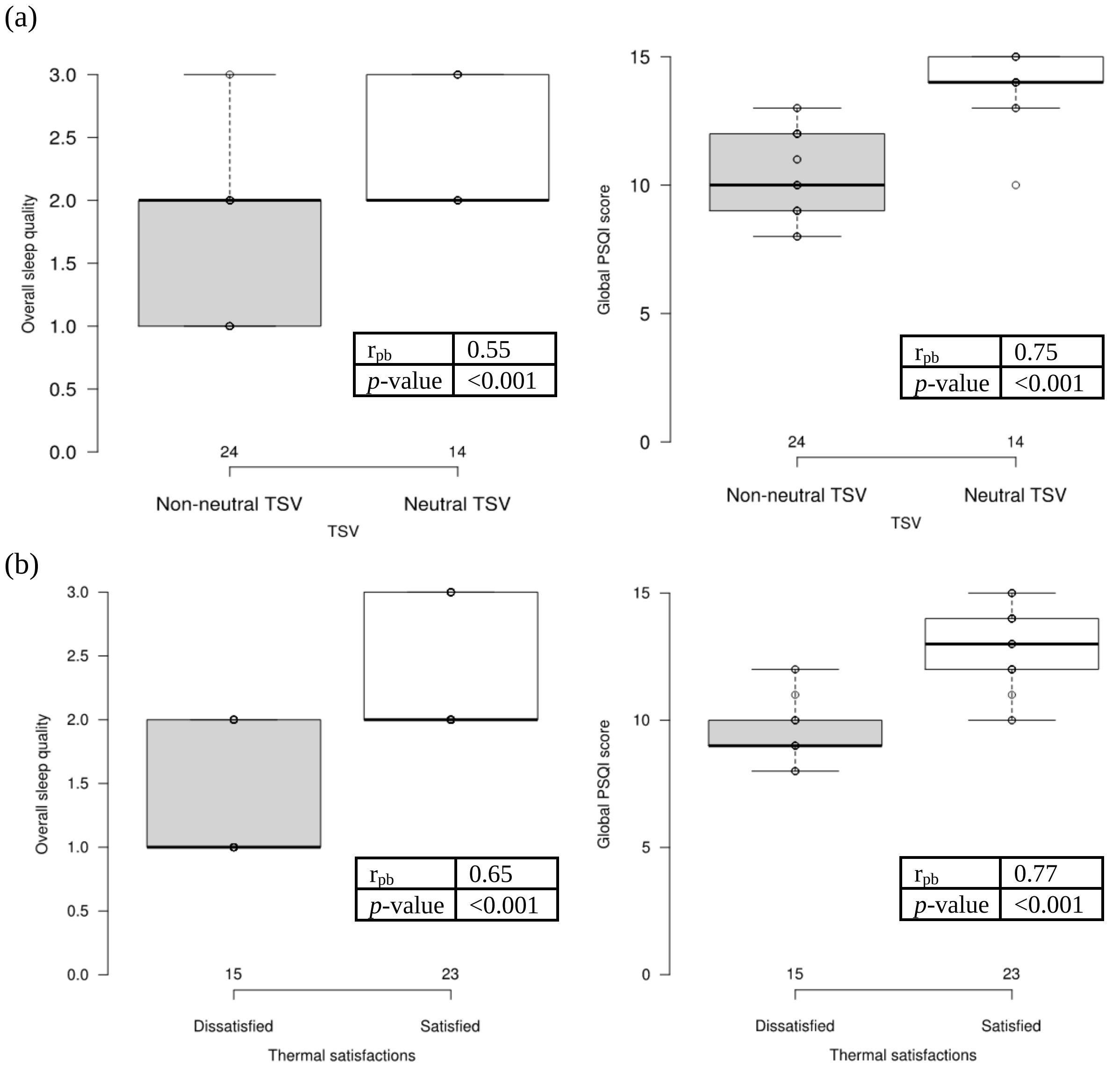

Figure 5. Overall sleep quality and global PSQI score of (a) neutral and non-neutral TSV groups; and (b) thermally dissatisfied and satisfied groups.

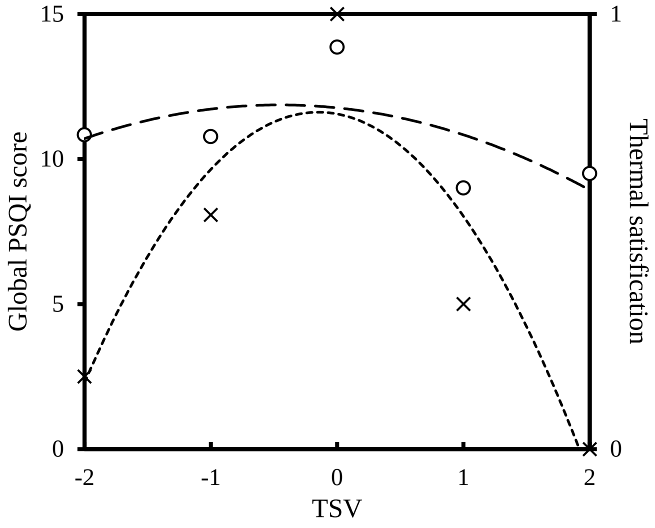

Figure 6. Average global PSQI score and thermal satisfaction at various TSV.

4. Discussion

4.1. Gender difference

Results suggest some degree of gender difference in sleeping thermal comfort. Although the environmental conditions experienced by students of both genders were statistically the same, the bedding system (bedding and coverage percentage) chosen by female students generally provided a higher total thermal resistance. As females have a 23% lower resting metabolic rate than males due to body mass composition, peak oxygen uptake and gender difference [39], higher thermal resistance is needed to maintain their core body temperature. Females are also found to be more sensitive to cool environment, whereas warm environments are less tolerable to males [40].

Besides having different responses towards the same perceived thermal condition due to physiological difference of the two genders, gender-specific psychological difference could also be the cause of distinct choice of bedding system. A high coverage percentage may provide females with a sense of comfort, as research has linked the use of weighted blanket to improved sleep quality, potentially due to the increase of serotonin, a neurotransmitter that lowers anxiety and produces a calming effects [41,42]. Male students, on the other hand, would adjust the thermal resistance accordingly for a desired thermal condition for sleep onset. These findings suggest that bedding system chosen by male students was mainly associated with ambient thermal condition, while female students would select the preferred thermal insulation according to their own preference in addition to thermal need.

4.2. Predictions by sleeping thermal comfort models

4.2.1. Thermal sensation

Subjective sensation results showed that existing models cannot accurately predict actual thermal sensation. TSV was, unexpectedly, found to be negatively correlated with the PMVs predicted by selected models. Figure 3(b) exhibits a strong positive correlation between total insulation values and PMVs, indicating that PMVs given by both prediction models depended largely on the total clothing value.

On the other hand, TSV was negatively associated with clothing value, which seems to be unorthodox to thermal comfort belief, given that a positive correlation between TSV and operative temperature was observed and shown in Figure 4(a). The result concurs with studies that observed dissimilar physiology in sleeping and awakening state. Candas et al. [43] and Jennings et al. [44] suggested that thermal sensitivity is greatly reduced during REM compared to NREM stage and wakefulness. Sweat onset is delayed and sweat rate is decreased during REM, leading to a reduced heat dissipation by evaporation and heat tolerance [45,46]. Moreover, a constant skin temperature was assumed in the models. Skin temperature variation has been found to play crucial role in heat dissipation for sleep onset, acting as an input signal for sleep regulation and maintaining SWS [47]. These findings indicate that conventional belief of thermal load provided is not applicable to sleeping person. Parameters in relation to heat flow and heat loss from body during sleep with bedding system are therefore needed to be identified by experiment.

In addition to the difference between thermal load due to dissimilar physiology in sleeping and awakening state, behavioral thermoregulation during sleep cannot be explained by physical sleeping thermal comfort models. Clothing values of bedding system estimated by immobile thermal manikin [28] are not able to reflect the actual thermal resistance since sleeping person may adjust his posture throughout the night. During awakening state, constant adjustment of clothing insulation can be done according to thermal condition to maintain a neutral thermal sensation. During sleeping state, one may adjust the coverage percentage of body, especially on area with higher thermal sensitivity, according to changing indoor temperature [48]. Sleeping individual may also change from supine position to lateral position when the bed climate is hot [49], allowing effective local cooling of back by heat dissipation in proximal area [50,51]. Nevertheless, behavioral adjustment may be delayed, limited or even lacking at various sleeping stage [16]. It is therefore necessary to explore further on clothing insulation and behavioral adjustment during sleep in order to determine the sleeping thermal sensation.

Besides, existing sleeping thermal comfort models may overestimate the effect of ambient thermal condition on sleeping thermal sensation. Even though a positive correlation between operative temperature and TSV was observed in this study, multiple studies have suggested that bed microclimate has a greater effect on thermal comfort and sensation during sleep period than ambient thermal condition [27,52]. Bischof et al. [53] illustrated from experiment that large variation in bedding microclimate could exist even under the same ambient conditions. Therefore, a comprehensive approach would be to study the bedding environment as a whole rather than the ambient environment.

4.2.2. Neutral temperature

Neutral temperatures given in this study (23.05°C or 23.81°C) agree with the sleeping thermal comfort study conducted in winter by Pan et al. [21], which suggested that at the given bedding system similar to this study, 23°C was the optimal condition for shortest sleep latency and maintaining deep sleep. However, this neutral temperature was much higher than the comfort temperature (<18°C) predicted by both sleep thermal comfort models at 3.58 clo. The underestimated neutral temperatures by models echo with the overestimation of thermal sensations. The discrepancy may be due to the assumption in the models that the sleeping thermal comfort requirement (i.e. α value) can be extrapolate to a lower metabolic rate of 40 W/m^2. This linear relationship between thermal load and thermal sensation may even be incorrect, as suggested by many research focusing on physiological response towards thermal conditions, responses towards cold and hot exposure of an individual is asymmetrical [54-56].

A recent experimental study of local body thermal condition for sleeping comfort suggested that the thermal sensation in sleeping state and waking state were different under the same thermal environment [20]. Lan et al. [18] also found that under the same thermal environment, subject’s thermal sensation decreased when they were asleep. The difference in thermal sensation may be explained by the decrease in core body temperature during sleep induced by underlying circadian rhythm that allows greater blood flow to the skin, thus enhancing heat loss to the environment [12,57-59]. In addition, local body cooling at back and head was found to be effectively improve thermal comfort and sleep quality in hot environment [60] All these findings indicate that thermal sensation during sleep is distinct and localized. It is essential for sleeping thermal comfort to address the discrepancies.

4.3. Sleep quality and thermal comfort

Many have discussed the correlation between ambient temperature and sleep quality with diverse results and opinions. For example Pan et al. [21] confirmed from a sleep chamber experiment that subjective and objective sleep quality was the best at 23°C and worst at 17°C. Wang et al. [27] instead suggested sleep quality was highest at an operative temperature of 15.8°C. A low ambient temperature was also preferred by young adults in sleep experiment by Liu et al. [61]. In fact, discussing sleep quality only with ambient temperature may not be appropriate as positive effect of bed cover and quilt on cold exposure is often ignored. Bedding system can sustain an isolated high temperature bed microclimate for maintaining high level of skin blood flow and skin temperature, leading to better thermal sensation in cold exposure [47]. High skin temperature was also associated with increased activity of warm-sensitive neurons (WSNs) for regulating NREM sleep and the induction of sleep [47,63], therefore promoting good sleep quality. Body part covered by bedding system was found to be less sensitive to ambient temperature, and a mean bed temperature around 31 °C was deemed thermally natural and comfortable [52].

Because of the abovementioned reason, in this study, association between thermal comfort and sleep quality was investigated instead of ambient temperature. Both thermally satisfied students and students with neutral thermal sensation had significantly higher self-assessed overall sleep quality and global PSQI score, with statistically significant positive association indicated by point-biserial correlation coefficient, suggesting that sleep quality was largely influenced by thermal comfort.

Average global PSQI score and thermal satisfaction at various TSV (Figure) indicates that students who felt cold were less dissatisfied and had a better sleep quality than those who felt hot. This result revealed an interesting phenomenon that sleeping people have different physiological and psychological reactions towards hot and cold environments. In fact, mixed viewpoints towards the effects of cold and heat exposure on sleep quality were concluded from various studies, which can be caused by difference in experimental characteristics including subject’s ethnicity and climate [63]. Some research suggested that cold exposure disrupts sleep more than heat exposure for naked subject [19,55]. However for subjects with bedding system, increase toleration to cold air and improved sleep quality were observed [14]. Cold exposure at 21°C increased wakefulness and decreased stage 2 sleep without affecting other sleep stages [15]. It was also found that cold exposure significantly altered heart rate variability in stage 2 and SWS but did not affect sleep efficiency, duration and percentage spend for each sleep stage. This change might even occur without any subjective sensation [16]. A number of studies found no significant difference in sleep quality with temperature ranging from 9°C to 20°C [16], 13°C to 23°C [64] and 3°C to 17°C [65], suggesting with adequate clothing insulation to maintain a constant bed climate, cold exposure does not affect sleep much.

With bedding system, heat exposure may pose more disturbance to sleep than cold exposure, as suggested by Okamoto-Mizuno and Tsuzuki [64] and Okamoto-Mizuno and Mizuno [66]. In heat exposure at about 35°C, shortened sleep duration and increased wakefulness was observed [67]. It is also common to see a decrease in SWS and REM in hot sleeping environment [68]. People may adopt behavioral thermoregulation to reduce heat stress, for example changing sleeping posture, use of air flow to reduce heat stress, etc. [69]. However, these behavioral thermoregulations in mid-sleep indicate wakefulness [70] and therefore degrading the sleep quality.

4.4. Limitations and Future work

Despite that some statically significant findings regarding sleeping thermal comfort and sleep quality were identified, the fact that the results were concluded from a relatively small sample size (N = 38), narrow demographic range (university students of age 18–25) and not in a controlled environment cannot be ignored. Other environmental factors that may have influences on sleep quality were not considered in this study. No physical indicators, for example electroencephalogram (EEG), skin temperature, etc., were measure during sleep. Results were based on students recall in memory of thermal sensation and sleep quality immediately after they woke up, which were in subjective nature. Subjective questionnaire may only be able to capture sensation from a small part of sleep period close to awakening.

This study revealed that sleeping thermal comfort models could not accurately predict actual thermal sensation. Since most of living environments are designed to accommodate people when they are awake, sleeping environment is constantly ignored. Yet, we spend almost one-third of time sleeping, which is vital in regaining energy and also greatly affects our next-day performance. Therefore, in the future, there is a need to develop another thermal comfort model for sleeping instead of relating sleeping thermal load to Fanger's PMV expression. The model shall address the distinct characteristics of thermal sensation during sleep. It is recommended to study the bedding environment as a whole rather than just the ambient environment. We also agree with Lan et al. [19] that much work needs to be done on defining a thermally comfortable sleeping environment.

5. Conclusion

Sleep is essential to everyone and can be largely affected by poor thermal environment. However, research into thermal comfort in sleeping environment is limited. Linkage between thermal satisfaction and sleep quality had not been identified. This study investigated the relationship between thermal environment, sleeping thermal sensation, thermal satisfaction and sleep quality in a university dorm in Hong Kong. Results showed that under the same thermal environment, female students generally opted for a bedding system with higher total thermal resistance, which might not be for the purpose of maintaining body temperature, but instead for a sense of comfort and better sleep quality.

Both of the selected thermal sensation prediction models overestimated the thermal sensation and underestimated the neutral temperature, suggesting that Fanger's PMV expression, which was based on awaken people, is not be applicable to sleeping individuals due to difference in thermal sensation in the two states. The following reasons were identified:

- dissimilar physiology in sleeping and awakening state
- behavioral thermoregulation
- overestimation of the effect of ambient thermal condition on sleeping thermal sensation
- asymmetrical thermal sensation towards cold and hot exposure
- localized thermal sensation during sleep

Student's self-assessed overall sleep quality was positivity linked with mid-sleep/ early awakenings, refreshment and duration of sleep. Both thermally satisfied students and students with neutral thermal sensation had significantly higher self-assessed overall sleep quality and global PSQI score, suggesting that sleep quality was largely influenced by thermal comfort. Average global PSQI score and thermal satisfaction at various TSV indicates dissimilar reactions towards heat and cold exposure, possibly due to the use of adequate clothing insulation that maintain a constant and comfortable bed climate in cold environment, while behavioral thermoregulations in hot environment degrade sleep quality by increasing wakefulness.

Acknowledgement

This work was undertaken by the Department of Building Services Engineering, The Hong Kong Polytechnic University. It was partially supported the Research Grants Council of HKSAR and The Hong Kong Polytechnic University (Project no. 15208817, GYBFN).

References

1. Benington, J.H., & Heller, H.C. (1995). Restoration of brain energy metabolism as the function of sleep. Process in Neurobiology 45, 347-360.
2. Vyazovskiy, V.V., & Delogu, A. (2014). NREM and REM Sleep: Complementary Roles in Recovery after Wakefulness. The Neuroscientist 20(3), 203-219.
3. Xie, L., Kang, H., Xu, Q., Chen, M. J., Liao, Y., Thiyagarajan, M., O'Donnell, J., Christensen, D.J., Nicholson, C., Iliff, J.J., Takano, T., Deane, R., & Nedergaard, M. (2013). Sleep Drives Metabolite Clearance from the Adult Brain. Science, 342(6156), 373-377.
4. Luntamo, T., Sourander, A., Rihko, M., Aromaa, M., Helenius, H., Koskelainen, M., & McGrath, P. J. (2012). Psychosocial determinants of headache, abdominal pain, and sleep problems in a community sample of Finnish adolescents. European child & adolescent psychiatry, 21(6), 301-313.
5. Tkachenko, O., Olson, E. A., Weber, M., Preer, L. A., Gogel, H., & Killgore, W. D. (2014). Sleep difficulties are associated with increased symptoms of psychopathology. Experimental brain research, 232(5), 1567-1574.
6. McCoy, J. G., & Strecker, R. E. (2011). The cognitive cost of sleep lost. Neurobiology of learning and memory, 96(4), 564-582.
7. Sadeh, A., Gruber, R., & Raviv, A. (2002). Sleep, neurobehavioral functioning, and behavior problems in school-age children. Child development, 73(2), 405-417.
8. Knutson, K. L., Van Cauter, E., Rathouz, P. J., Yan, L. L., Hulley, S. B., Liu, K., & Lauderdale, D. S. (2009). Association between sleep and blood pressure in midlife: the CARDIA sleep study. Archives of internal medicine, 169(11), 1055-1061.
9. Narang, I., Manlhiot, C., Davies-Shaw, J., Gibson, D., Chahal, N., Stearne, K., Fisher, A., Dobbin, S., & McCrindle, B. W. (2012). Sleep disturbance and cardiovascular risk in adolescents. Cmaj, 184(17), E913-E920.
10. Tasali, E., Leproult, R., Ehrmann, D. A., & Van Cauter, E. (2008). Slow-wave sleep and the risk of type 2 diabetes in humans. Proceedings of the National Academy of Sciences, 105(3), 1044-1049.
11. Murphy, P.J., & Campbell, S.S. (1997). Nighttime Drop in Body Temperature: A Physiological Trigger for Sleep Onset? Sleep, 20(7), 505-511.
12. Kräuchi, K., Cajochen, C., Werth, E., & Wirz-Justice, A. (1999). Warm feet promote the rapid onset of sleep. Nature 401, 36-37.
13. Okamoto-Mizuno, K., Mizuno, K., Michie, S., Maeda, A., & lizuka, S. (1999). Effects of humid heat exposure on human sleep stages and body temperature. Sleep, 22(6), 767-773.
14. Tsuzuki, K., Mori, I., Sakoi, T., & Kurokawa, Y. (2015). Effects of seasonal illumination and thermal environments on sleep in elderly men. Building and Environment, 88, 82-88.
15. Palca, J.W., Walker, J.M., & Berger, R.J. (1986). Thermoregulation, metabolism, and stages of sleep in cold-exposed men. Journal of Applied Physiology, 61(3), 940-947.
16. Okamoto-Mizuno, K., Tsuzuki, K., Mizuno, K., & Ohshiro, Y. (2009). Effects of low ambient temperature on heart rate variability during sleep in humans. European Journal of Applied Physiology, 105, 191-197.
17. Viola, A.U., Simon, C., Ehrhart, J., Geny, B., Piquard, F., Muzet, A., & bBrandenberger, G. (2002). Sleep processes exert a predominant influence on the 24-h profile of heart rate variability. Journal of Biological Rhythms 17, 539-547.

18. Lan, L., Pan, L., Lian, Z.W., Huang, H.Y., & Lin, Y.B. (2014). Experimental study on thermal comfort of sleeping people at different air temperatures. Building and Environment 73, 24-31.
19. Lan, L., Tsuzuki, K., Liu, Y.F., & Lian, Z.W. (2017). Thermal environment and sleep quality: A review. Energy and Buildings 149, 101-113.
20. Song, C., Liu, Y.F., Zhu, X.J., Wang, D.J., Wang, Y.Y., & Liu, J. P. (2020). Identification of local thermal conditions for sleeping comfort improvement in neutral to cold indoor thermal environments. Journal of Thermal Biology, 87, 102480.
21. Pan, L., Lian, Z.W., & Lan, L. (2012). Investigation of sleep quality under different temperatures based on subjective and physiological measurements. HVAC&R Research, 18(5), 1030-1043.
22. Zhang, N., Cao, B., & Zhu, Y.X. (2018). Indoor environment and sleep quality: a research based on online survey and field study. Building and Environment 137, 198-207.
23. Lin, Z.P., & Deng, S.M. (2008). A study on the thermal comfort in sleeping environments in the subtropics – Developing a thermal comfort model for sleeping environments. Building and Environment, 43, 70-81.
24. Fanger, P.O. (1980). Thermal comfort. Copenhagen: Danish Technical Press.
25. Lan, L., Zhai, Z.Q., & Lian, Z.W. (2018). A two-part model for evaluation of thermal neutrality for sleeping people. Building and Environment, 132, 319-326.
26. Chen. Y., Guo, Y., Shem, L., & Liu, S. (2013). The quantitative effects of mattress and sleep postures on sleep quality. International Asia Conference on Industrial Engineering and Management Innovation (IEMI2012) Proceedings, 107-115.
27. Wang, Y.Y., Liu, Y. F., Song, C., & Liu, J. P. (2015). Appropriate indoor operative temperature and bedding micro climate temperature that satisfies the requirements of sleep thermal comfort. Building and Environment, 92, 20-29.
28. Lin, Z.P., & Deng, S.M. (2008). A study on the thermal comfort in sleeping environments in the subtropics – Measuring the total insulation values for the bedding systems commonly used in the subtropics. Building and Environment 43, 905-916.
29. Libert, J.P., Bach, V., Johnson, L.C., Ehrhart, J., Wittersheim, G., & Keller, D. (1991). Relative and combined effects of heat and noise exposure on sleep in humans. Sleep 14(1), 24-31.
30. ASHRAE. (2017). ANSI/ASHRAE Standard 55-2017 – Thermal environmental conditions for human occupant.
31. Buysse, D.J., Reynolds III, C.F., Monk, T.H., Berman, S.R., & Kupfer, D.J. (1989). The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. Journal of Psychiatric Research, 28(2), 193-213.
32. Gagge, A.P., Fobelets, A.P., & Berglund, L.G. (1986). A standard predictive index of human response to the thermal environment. ASHRAE Transactions, 92(Pt. 2B), 709-31.
33. ASHRAE. (2001). ASHRAE handbook of fundamentals.
34. Zhao, S. S., Liu, Y. M., & Yao, J. B. (1984). The estimation of body surface area of adults Chinese male. Acta Nutrimenta Sinica, 6(2), 87-95.
35. Zhao, S. S., Liu, Y. M., & Yao, J. B. (1987). The estimation of body surface area of adults Chinese females. Acta Nutrimenta Sinica, 9(3), 200-207.
36. Douglas, N.J., White, D.P., Pickett, C.K., Weil, J.V., & Zwillich, C.W. (1982). Respiration during sleep in normal man. Thorax, 37, 840-844.
37. McCutchan, J.W., & Taylor, C.L. (1951). Respiratory heat exchange with varying temperature and humidity of inspired air. Journal of Applied Physiology, 4(2), 121-135.

38. Wong, L.T., Fong, K. N. K., Mui, K.W., Wong, W. W. Y., Lee, L. W. (2009). A field survey of the expected desirable thermal environment for older people. Indoor and Built Environment 18(4), 336-345.
39. Arciero, P.J., Goran, M.I., & Poehlman, E.T. (1993). Resting metabolic rate is lower in women than in men. Journal of Applied Physiology 75(6), 2514-2520.
40. Pan, L., Lian, Z.W., & Lan, L. (2012). Investigation of gender differences in sleeping comfort at different environmental temperatures. Indoor and Built Environment 21(6), 811-820.
41. Ackerley, R., Badre, G., & Olausson, H. (2015). Positive effects of a weighted blanket on insomnia. Journal of Sleep Medicine & Disorders, 2(3), 1-7.
42. Gee, B. M., Peterson, T. G., Buck, A., & Lloyd, K. (2016). Improving sleep quality using weighted blankets among young children with an autism spectrum disorder. International Journal of Therapy and Rehabilitation, 23(4), 173-181.
43. Candas, V., Libert, J.P., & Muzet, A. (1982). Heating and cooling stimulations during SWS and REM sleep in man. Journal of Thermal Biology 7, 155-158.
44. Jennings, J.R., Reynolds, C.F., Bryant, D.S., Berman, S.R., Buysse, D.J., Dahl, R.E., Hoch, C.C., & Monk, T.H. (1993). Peripheral thermal responsivity to facial cooling during sleep. Psychophysiology 30, 374-382.
45. Libert, J.P., Candas, V., Muzet, A., & Ehrhart, J. (1982). Thermoregulatory adjustments to thermal transients during slow wave sleep and REM sleep in man. Journal of Physiology (Paris) 78, 251-257.
46. Sagot, J.C., Amoros, C., Candas, V., Libert, J.P. (1987). Sweating responses and body temperatures during nocturnal sleep in humans. American Journal of Physiology 252, R462-R470.
47. Van Someren, E. J. (2000). More than a marker: interaction between circadian regulation of temperature and sleep age-related changes, and treatment possibilities. Chronobiology International 17(3), 313-354.
48. Okamoto-Mizuno, K., Tsuzuki, K., & Mizuno, K. (2003). Effects of head cooling on human sleep stages and body temperature. International Journal of Biometeorology 48(2):98-102.
49. Miyazawa, M. (1976). On the correlation between bed climate influenced by combinations of mattresses and sleep. Research Journal of Living Science, 23, 86-91.
50. Tan, S.H., Shen, T.Y., & Wu, F.G. (2015). Design of an innovative mattress to improve sleep thermal comfort based on sleep positions. Procedia Manufacturing 3, 5834-5844.
51. Qian, X.L., Lan, L., & Xiong, J. (2017). Effect of local cooling on thermal comfort of people in a sleeping posture. Procedia Engineering 205, 3277-3284.
52. Song, C., Liu, Y.F., Zhou, X.J., & Liu J.P. (2015). Investigation of human thermal comfort in sleeping environments based on the effects of bed climates. Procedia Engineering 121, 1126-1132.
53. Bischof, W., Madsen, T.L., Clausen, J., Madsen, P.L., WildschiØdtz, G. (1993). Sleep and the temperature field of the bed. Journal of Thermal Biology 18(5-6), 393-398.
54. Haskell, E.H., Palca, J.W., Walker, J.M., Berger, R.J., & Heller, H.C. (1981a). Metabolism and thermoregulation during stages of sleep in humans exposed to heat and cold. Journal of Applied Physiology 51, 948-954.
55. Haskell, E.H., Palca, J.W., Walker, J.M., Berger, R.J., Heller, H.C. (1981b). The effects of high and low ambient temperatures on human sleep stages. Electroencephalography and Clinical Neurophysiology 51, 494-501.
56. Okamoto-Mizuno, K., & Mizuno, K. (2012). Effects of thermal environment on sleep and circadian rhythm. Journal of Physiological Anthropology 31, 14.

57. Barrett, J., Lack, L., & Morris, M. (1993). The sleep-evoked decrease of body temperature. Sleep 16, 93-99.
58. Kräuchi, K., Cajochen, C., Werth, E., & Wirz-Justice, A. (2000). Functional link between distal vasodilation and sleep-onset latency? American Journal of Physiology-Regulatory, Integrative and Comparative Physiology 278, R741-R748.
59. Lack, L., & Gradisar, M. (2002). Acute finger temperature changes preceding sleep onsets over a 45-h period. Journal of Sleep Research 11, 275-282.
60. Lan, L., Qian, X.L., Lian, Z.W., & Lin, Y.B. (2018). Local body cooling to improve sleep quality and thermal comfort in a hot environment. Indoor Air 28(1), 135-145.
61. Liu, Y., Song, C., Wang, Y., Wang, D., & Liu, J. (2014). Experimental study and evaluation of the thermal environment for sleeping. Building and Environment 82, 546-555.
62. McGinty, D., & Szymusiak, R. (2001). Brain structures and mechanisms involved in the generation of NREM sleep: focus on the preoptic hypothalamus. Sleep Medicine Reviews 5(4), 323-342.
63. Buguet, A. (2007). Sleep under extreme environments: Effects of heat and cold exposure, altitude, hyperbaric pressure and microgravity in space. Journal of the Neurological Sciences 262(1-2), 145-152.
64. Muzet, A., Libert, J.P., & Candas, V. (1984). Ambient temperature and human sleep. Experientia 40, 425-429.
65. Okamoto-Mizuno, K., & Tsuzuki, K. (2010). Effects of season on sleep and skin temperature in the elderly. International Journal of Biometeorology 54, 401–409.
66. Okamoto-Mizuno, K., & Mizuno, K. (2011). Sleep and environment. Treatment Strategies - Respiratory 2, 87-89.
67. Libert, J.P., Di Nisi, J., Fukuda, H., Muzet, A., Ehrhart, J., & Amoros, C. (1988). Effect of continuous heat exposure on sleep stages in humans. Sleep 11, 195-209.
68. Karacan, I., Thornby, J.I., Anch, A.M., Williams, R.L., & Perkins, H.M. (1978). Effects of high ambient temperature on sleep in young men. Aviation, Space, and Environmental Medicine 49, 855–860.
69. Tsuzuki, K., Okamoto-Mizuno, K., Mizuno, K., & Iwaki, T. (2008). Effects of airflow on body temperatures and sleep stages in a warm humid climate. International Journal of Biometeorology 52(4), 261-270.
70. Parmeggiani, P.L. (1987). Interaction between sleep and thermoregulation: an aspect of the control of behavioral states. Sleep 10(5), 426-35.
71. Lan, L., Lian, Z. W., Qian, X. L., & Dai C. Z. (2016). The effects of programmed air temperature changes on sleep quality and energy saving in bedroom. Energy and Buildings 129, 207-214.

    Califano, R., Naddeo, A., & Vink, P. (2017). The effect of human-mattress interface's temperature on perceived thermal comfort. Applied Ergonomic 58, 334-341