

A Study of The Effect of Thermal Environment on The Thermal Comfort of Human Sleep

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Abstract: In this study, the research method of field experimental test and questionnaire survey was used to select college students without sleep disorders as experimental subjects, and to study the influence patterns of different sleep thermal environments (22°C, 26°C, 30°C) on thermophysiological parameters and sleep quality of the subjects. The results of the study showed that the thermophysiological parameters and sleep quality of the subjects were significantly different in different sleep thermal environments. The mean skin temperature of the subjects during sleep showed the same trend of change in different thermal environments, and its mean value increased significantly with the increase of ambient temperature, and there was less individual variability in the skin temperature change of the subjects in the neutral environment (26°C), which made their sleep smoother; the blood oxygen saturation decreased with the increase of ambient temperature, and the change of the heart rate was correlated with the quality of sleep of the subjects. Sleep quality was highest in neutral environments, next in colder environments (22°C), and worst in hotter environments (30°C). The mean skin temperature of the subjects changed according to the stage of sleep: the deeper the sleep, the lower the skin temperature, and the lighter the sleep, the higher the skin temperature.

Keywords: Sleep thermal comfort; Thermophysiological response; Sleep quality; Sleep thermal environment.

1. Introduction

Sleep is the most basic human need, and quality sleep is also an important way to ensure good health and quality of life [1-3]. A healthy adult needs at least 8 hours of quality sleep to maintain sufficient vigor. However, about 20-30% of the global population is severely affected by insomnia due to the effects of uncomfortable sleep thermal environments [4]. Sleep disorders have become a major challenge to human health.

Sleep thermal environment is one of the key factors affecting sleep quality. A suitable sleep thermal environment can shorten the time to fall asleep and prevent nocturnal awakenings, thus improving sleep quality [5,6]. Sleep surveys for preschool children [7] showed that the total sleep duration of preschool children was longest at an ambient temperature of 22.2°C, which is the most suitable temperature for the sleep thermal environment. A study by Candas [8] et al. demonstrated that the comforter temperature stabilized between 28.6°C and 30.9°C when the room temperature ranged from 16°C to 25°C, and that when the outside temperature was 19°C or 22°C, the At 19°C or 22°C, the ambient temperature was maintained at 29.6°C. The study also showed that the room temperature was optimal at around 19°C, and that subjective questionnaires showed a significant increase in discomfort when the room temperature was deviated from this temperature. The above studies have shown that a comfortable thermal sleep environment has a significant effect on improving sleep quality, but the studies have only examined some of the conditions and have not examined the effects of the thermal sleep environment on sleep quality during the whole process of human sleep. During sleep, there are significant changes in the average skin temperature of the human body as influenced by the ambient

temperature, and an increase in the ambient temperature leads to an increase in the overall average skin temperature level [9,10]. This indicates that there is a close link between mean skin temperature and the thermal environment of sleep; in the resting state, the heart rate of a normal person, i.e., the number of heartbeats per minute, fluctuates in the range of 60-100 beats per minute (bpm) [11], and after entering the sleep state, the heart rate is usually reduced by 10-20 beats per minute compared with the resting state. Heart rate is dually regulated by the autonomic and thermoregulatory systems, so there is a link between heart rate and thermal environment: heart rate tends to be higher in low-temperature than in high-temperature environments [12]. Oxygen saturation is the volume of oxygenated hemoglobin bound by oxygen in the blood as a percentage of the volume of all bindable hemoglobin [13]. Relevant studies have found that the higher the temperature at the wound, the lower the blood oxygen saturation [14], which suggests that there is a certain correlation between blood oxygen saturation and the thermal environment, and therefore the measurement of blood oxygen saturation can be used as an important reference basis for assessing the effects of the thermal environment on the human body. The above studies have shown that during sleep, changes in the sleep thermal environment trigger corresponding changes in thermophysiological parameters of the human body. However, there is a lack of research on the underlying mechanisms of such changes and their association with sleep thermal comfort.

Based on the above problems and deficiencies, this study combines physiological parameters and subjective questionnaire evaluation to conduct sleep experiments on school students to investigate the effects of different sleep thermal environments on human thermal comfort, and to propose a range of the most comfortable sleep thermal

environments to satisfy people's requirements for sleep thermal comfort and to improve sleep quality.

1.1. Method

1.1.1. Experimental environment

In order to reduce the impact of the sleep place on the experimenter's sleep quality, the experiment selected a single

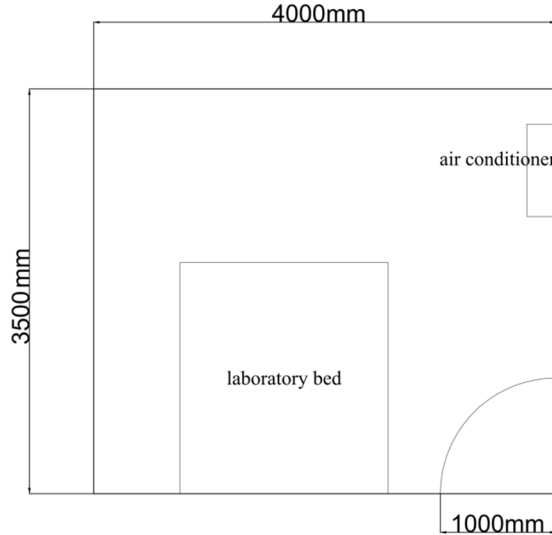


Figure 1. Schematic diagram of room plan and mattress system

1.1.2. Environmental Parameters Measuring Instruments

Indoor and outdoor environment temperature and humidity: 2 temperature and humidity testers (Jiali), temperature measurement range is $-40^{\circ}\text{C}\sim 125^{\circ}\text{C}$, measurement accuracy is $\pm 0.2^{\circ}\text{C}$; humidity measurement range is $0\% \sim 100\%$, measurement accuracy is $\pm 2.0\%$. They were placed in the indoor and outdoor environments respectively, and the temperature and humidity of the indoor and outdoor environments were recorded every minute, and the temperature and humidity of the indoor environments were measured at a position of 50-60 cm from the subject's body.

Air velocity at air-conditioning outlet: Sigma Split Anemometer (AS-8336), measuring air velocity range 0-

room similar to the environment of the student dormitory as the experimental environment, the room is equipped with air-conditioning equipment to control the indoor temperature, in order to achieve the purpose of controlling the experimental variables, the room plane and the experimental bed mattress system schematic diagram as shown in Figure 1.

45m/s, measuring accuracy 0.001m/s. The maximum and minimum air velocity at the air-conditioning outlet were measured at the beginning of the experiment.

1.2. Subject selection criteria

Six male and six female subjects each were selected for this experiment, for a total of 12 subjects to participate in the test, with an age range of 22 to 26 years. The details are shown in Table 1. These subjects had relatively consistent sleep rhythms and did not experience sleep disorders. In this study, the Pittsburgh Sleep Quality Index (PSQI) was used to assess the subjects' sleep status in the last month, and only subjects with a score of no more than 5 were selected to participate in the subsequent experiments.

Table 1. Subject specifics information

	Statistical projects	Male	Female	Totals
Age (year)	Maximum values	24	26	26
	Minimum value	23	22	22
	Average value	23.83	23.83	23.83
Height (cm)	Maximum values	175	168	175
	Minimum value	168	158	158
	Average value	171.83	163.66	167.75
Weight (kg)	Maximum values	107	70	107
	Minimum value	56	47	47
	Average value	73.16	57.33	65.25

The bed size used by the subjects during the experiment was uniformly $190\text{cm}\times 120\text{cm}$, and the subjects were also required to use the same quilt and wear the same disposable short-sleeved pyjamas and pyjama trousers during the experiment. In this way, the thermal resistance of the clothing and mattress system can be effectively controlled to ensure the stability of the experimental variables. Disposable sheets,

covers and pillowcases were replaced after each experiment to ensure a clean and hygienic experimental environment.

1.3. Instruments and methods for measuring physiological parameters

1) Skin temperature and humidity: 8 button type miniature skin temperature and humidity sensors (iButton DS1923),

with a temperature measurement range of $-20\sim 85^{\circ}\text{C}$ and a measurement accuracy of $\pm 0.1^{\circ}\text{C}$; and a humidity measurement range of $0\% \sim 100\% \text{RH}$ and a measurement accuracy of $\pm 0.5\%$. They were placed on seven parts of the subject's forehead, chest, forearm, back of hand, thigh, calf, and instep respectively, and the skin temperature and humidity were measured every two minutes. Measurement was started at the beginning of the experiment and stopped at the end of the experiment, thus obtaining the skin temperature of the subject throughout the sleeping time. Then based on the skin temperature values of each part, the seven-point method of Equation (1) was used to calculate the subject's mean skin temperature (MST) [15], to obtain the change of the average skin temperature of the human body during sleep.

$$MST = 0.07T_{Forehead} + 0.35T_{Chest} + 0.14T_{Forearm} + 0.05T_{Hand} + 0.19T_{Thigh} + 0.13T_{Calf} + 0.07T_{Foot} \quad (1)$$

Where, MST is the mean skin temperature, $^{\circ}\text{C}$; $T_{Forehead}$ is the forehead skin temperature, $^{\circ}\text{C}$; T_{Chest} is the chest skin temperature, $^{\circ}\text{C}$; $T_{Forearm}$ is the forearm skin temperature, $^{\circ}\text{C}$; T_{Hand} is the hand skin temperature, $^{\circ}\text{C}$; T_{Thigh} is the thigh skin temperature, $^{\circ}\text{C}$; T_{Calf} is the calf skin temperature, $^{\circ}\text{C}$; T_{Foot} is the foot skin temperature, $^{\circ}\text{C}$.

2) Heart rate and oxygen saturation: pulse oximetry finger ring (LOPE), oxygen saturation measurement range: $0\% \sim 100\%$, measurement accuracy $\pm 2\%$; heart rate $20 \sim 250 \text{bpm}$, measurement accuracy $\pm 2 \text{bpm}$. during the experiment, the subject wore it on the index finger, and it was measured once every second.

3) Using the Apple Series 6 sleep monitoring bracelet for sleep detection, subjects wore the bracelet before going to bed and then started the experiment. At the end of the experiment on the second day, the bracelet was removed, and the data from the bracelet was automatically synchronized to the

paired cell phone. The bracelet could accurately detect the specific duration and changes of each sleep stage, such as REM sleep, core sleep, deep sleep, and wakefulness time, during sleep, which was used as a reference for evaluating the subject's sleep quality.

4) In this study, the data obtained were analyzed using statistical methods of analysis, and the experimental data were analyzed using one-way repeated measures ANOVA for data that conformed to a normal distribution; for data that did not conform to a normal distribution, a Kruskal-Wallis one-way ANOVA was used and multiple comparisons were made by LSD post hoc analysis to further explore the two-by-two conditions of the differences. The significance level was set at 0.05.

1.4. Subjective evaluation scale design

The subjective sleep questionnaire in this experiment was divided into two parts: the pre-bedtime questionnaire collected the thermal sensations of the subjects' hands and feet before going to bed; the post-bedtime questionnaire mainly consisted of asking the subjects to recall the thermal environment sensations during last night's sleep, the thermal comfort situation as well as evaluating the quality of last night's sleep by answering a series of questions from the subjective sleep quality scale. The thermal sensation poll questionnaire and subjective sleep quality questionnaire are shown in the table below:

1) Hot Subjective Voting Questionnaire

The thermal subjective voting questionnaire includes thermal sensation and thermal comfort. The thermal sensation vote was measured using the seven levels of the ASHRAE standard [16], and the detailed explanation of the evaluation is shown in Table 2. The Thermal Comfort Vote is also assessed at seven levels: very uncomfortable (-3), uncomfortable (-2), slightly uncomfortable (-1), can't tell (0), just comfortable (1), comfortable (2), very comfortable (3).

Table 2. Hot Sensation Voting Evaluation Form

Scale	Meaning	Meaning	explanation
3		hot	Skin is completely moist, perspiration persists
2		warm	Start sweating
1		mildly warm	Feeling of heat, but not to the point of sweating
0		neuter	It's not hot and it's not cold.
-1		a little cool	Cold sensation, but no discomfort
-2		cool	have a desire to add more clothes to my wardrobe.
-3		cold	Occasional shivering and chills with cold bumps

Table 3. Subjective sleep quality evaluation form

Questions/Ratings	1	2	3	4	5
1.Level of restful or restless sleep	Very peaceful.	peaceful	Neither peaceful nor restless.	restless	Very fretful
2.Ease of falling asleep	very easy	easy	Neither easy nor difficult	difficult	Very difficult
3.Ease of waking up in the morning	very easy	easy	Neither easy nor difficult	difficult	Very difficult
4.The extent to which last night's sleep helped you regain your energy	Very good	good	ordinary	mediocre	very poor
5.Satisfaction with last night's sleep	Very satisfied	satisfied	ordinary	unsatisfactory	Very dissatisfied
6.Do you ever wake up in the night?	not	1 to 2 times	3 to 4 times	more times	
7.Did you get enough sleep last night?	enough	Not enough			

2) Subjective Sleep Quality Scale

Subjective sleep quality was referenced from the

questionnaire of Zilli [17] et al. Each questionnaire question featured multiple rating scales, with each option corresponding to a score, totaling 22 points. Lower scores represent better sleep quality. The subjective sleep quality evaluation scale is shown in Table 3:

1.5. Experimental procedure

In order to ensure the accuracy and continuity of the experimental data, and to ensure that the external environment does not undergo major changes, this study used the experimental method of repeated measurements, with each subject participating in three consecutive nights of experiments, and controlling the experimental ambient temperatures to be 22°C, 26°C, and 30°C, respectively. Each experiment started at 23:00 pm and ended at 7:00 am the next morning when 8 hours of standard sleep was achieved. The specific experimental procedure was as follows:

1) 21:30 Researchers arrived at the experimental site, turned on the air conditioner to preset the experimental temperature, and checked the experimental instruments to ensure that they could work properly.

2) 22:00 ~ 22:20 Subjects completed their personal hygiene and cleanliness, then arrived at the experimental site to sign in and sit down for a break.

3) 22:30 ~ 23:00 After the subjects had adapted to the experimental environment and their body temperature had stabilised, they put on the experimental equipment and checked whether the experimental apparatus was functioning properly, while the subjects made bedtime preparations and filled in the experimental-related questionnaires.

4) 23:00 After confirming that the experimental apparatus was working properly and the subjects were in normal condition, the researcher switched off the light and the sleep experiment started. During the sleep period, the researchers recorded and monitored the experimental data through the experimental apparatus.

5) 7:00 The researcher turned on the light, the subjects got up, filled in the thermal comfort and sleep quality questionnaire, removed the apparatus, saved the experimental data, and the experiment ended. The specific flow of the experiment is shown in Figure 2.

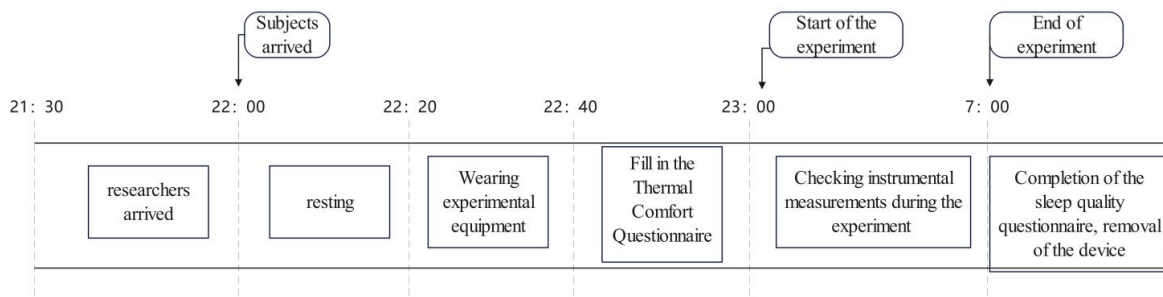


Figure 2. Schematic diagram of the experimental process

2. Results

2.1. Thermal Sensation Poll and Thermal Comfort Poll Results

The results of the comparison of the thermal sensation of the subjects' hands and feet at bedtime are shown in Figure 3, and there are significant differences in the thermal sensation of the subjects at bedtime under all three working conditions. When the ambient temperature was 22°C, the median thermal sensation score of the hand was close to 0, and the median

thermal sensation score of the foot was about 0.2, indicating that both the hand and the foot were in a relatively comfortable thermal sensation state at the current temperature, and the foot was slightly warmer than the hand; when the ambient temperature was 26°C, the thermal sensation scores of the hand and the foot were similar, and both were shown to be in a warm state; when the ambient temperature was 30°C, the hand and the foot were obviously feeling hot, and the degree of thermal sensation of the hands was higher than that of the feet.

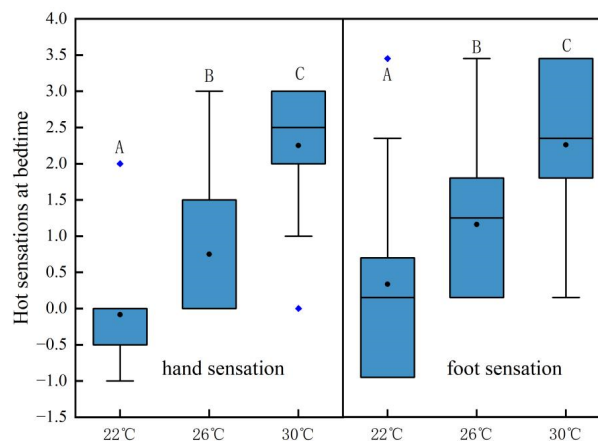


Figure 3. Comparison chart of the heat sensation of the subjects' hands and feet before going to bed in three different temperature environments

The results of the thermal sensation and thermal comfort polling of the subjects after waking up to the nighttime sleep

conditions are shown in Figures 4 and 5. Significant differences existed between the 22°C and 30°C and 26°C and

30°C temperature working conditions, and no significant differences existed between the 22°C and 26°C working conditions. Thermal sensory voting data showed that thermal sensory voting significantly increased during subjects' sleep as the ambient temperature working conditions changed from low to high, peaking when the ambient temperature was 30°C. Notably, the data measured at the three temperatures had a similar degree of dispersion, suggesting that subjects felt the

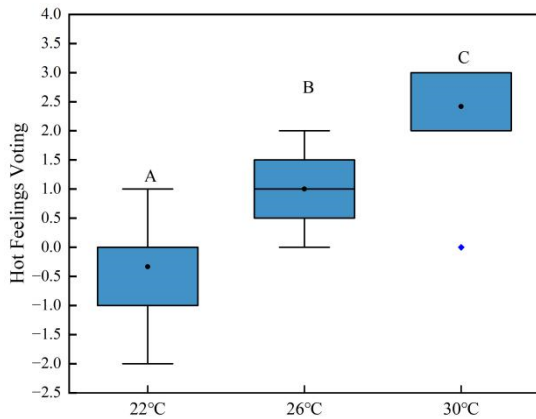


Figure 4. Voting on thermal sensation in subjects at different ambient temperatures

ambient temperature consistently. The thermal comfort vote results indicated that subjects generally found the sleeping environment more comfortable and the 26°C temperature environment more comfortable in the 22°C and 26°C environments, while the majority of subjects felt uncomfortable in the 30°C environment, but the degree of dispersion of the data was higher compared to the first two conditions.

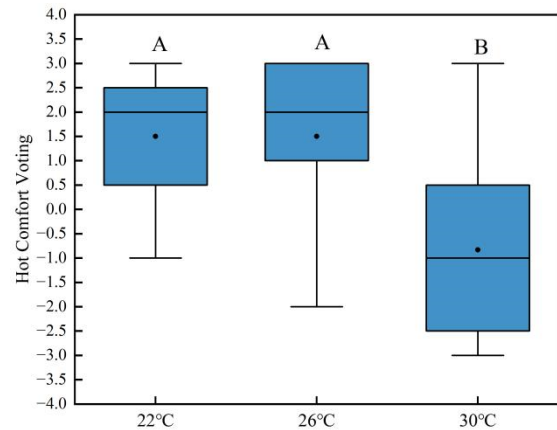


Figure 5. Thermal Comfort Voting for Subjects at Different Ambient Temperatures

2.2. Thermophysiological parameter

The average skin temperature changes during the whole process of the subjects' sleep are shown in Figure 6. The results showed that the average skin temperature was highest at 30°C, always higher than the other two working conditions; the trend of the average skin temperature change was roughly similar in the temperature environments of 22°C and 26°C; as a whole, the average skin temperatures in the three ambient temperatures had the same trend, i.e., the body temperature

increased rapidly to the peak within the first hour of laying down, then declined rapidly, and then finally leveled off in general. The changes in blood oxygen saturation of the subjects are shown in Figure 7. The results showed that blood oxygen saturation decreased with increasing ambient temperature. It was shown to be highest at 22°C and lowest at 30°C. The changes in heart rate of the subjects are shown in Figure 8. As the ambient temperature increased, the heart rate decreased and then increased, exhibiting the highest at 30°C and the lowest at 26°C.

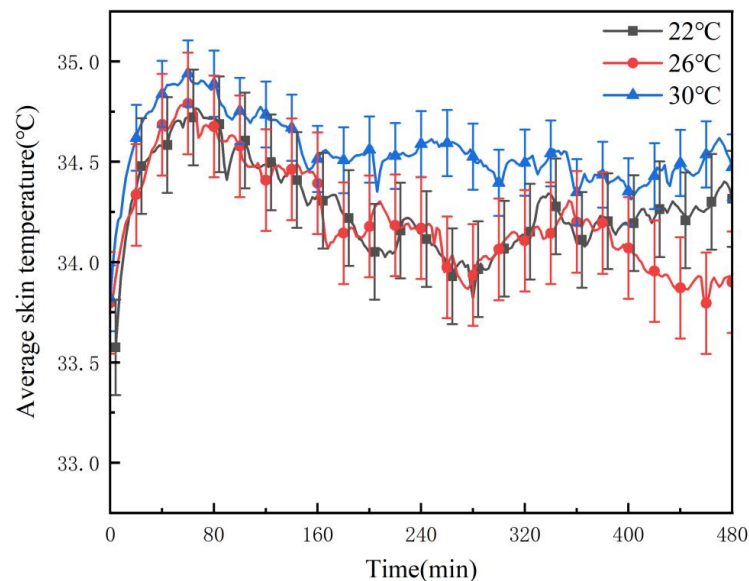


Figure 6. Changes in mean skin temperature throughout sleep in subjects with different temperature environments

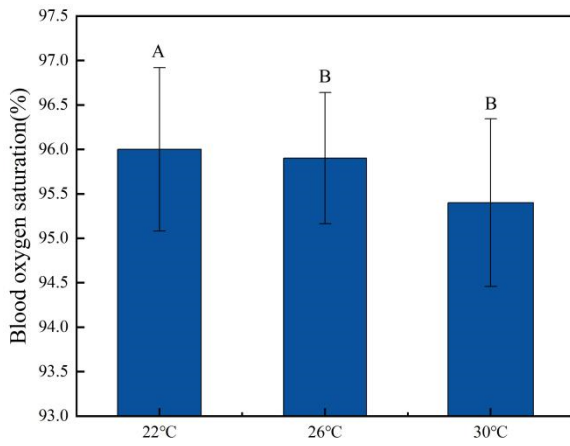


Figure 7. Graph of the change of subject's oxygen saturation at three ambient temperatures

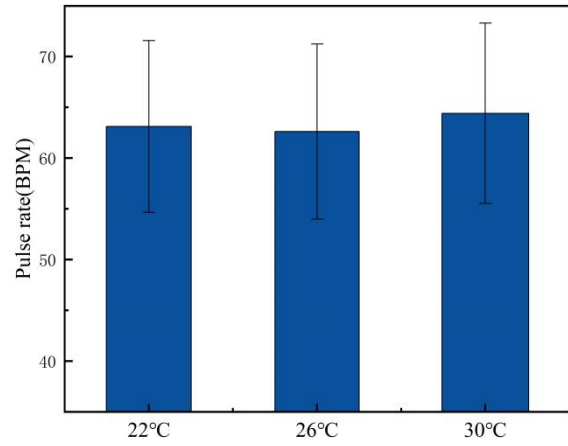


Figure 8. Graph of the subject's heart rate change at three ambient temperatures

2.3. Sleep quality

The results of the subjective sleep quality questionnaire scores are shown in Figure 9. There was a significant difference between the subjects' questionnaire scores in the 22°C and 30°C environments regarding the extent to which last night's sleep helped to restore energy, the degree of satisfaction with last night's sleep, and whether or not they felt that last night's sleep was sufficient for them to get back to their senses; there was a significant difference between the questionnaire scores of the degree of restfulness or restlessness of last night's sleep in the 26°C and 30°C environments; and there was a significant difference in the

results of subjective questionnaires on the degree of difficulty in awakening in the morning in all three temperature environments. significant differences. When the ambient temperature increased from 22°C to 30°C, all indicators changed significantly. Among them, the scores of four indicators, namely, the degree of help of sleep in restoring energy, the degree of satisfaction with nighttime sleep, the frequency of nighttime awakening and the sense of sleep adequacy, showed an increasing trend with increasing temperature; in the two indicators, namely, the degree of tranquility or agitation of last night's sleep and the degree of difficulty in falling asleep, the scores showed a change characteristic of low in the middle and high at both ends.

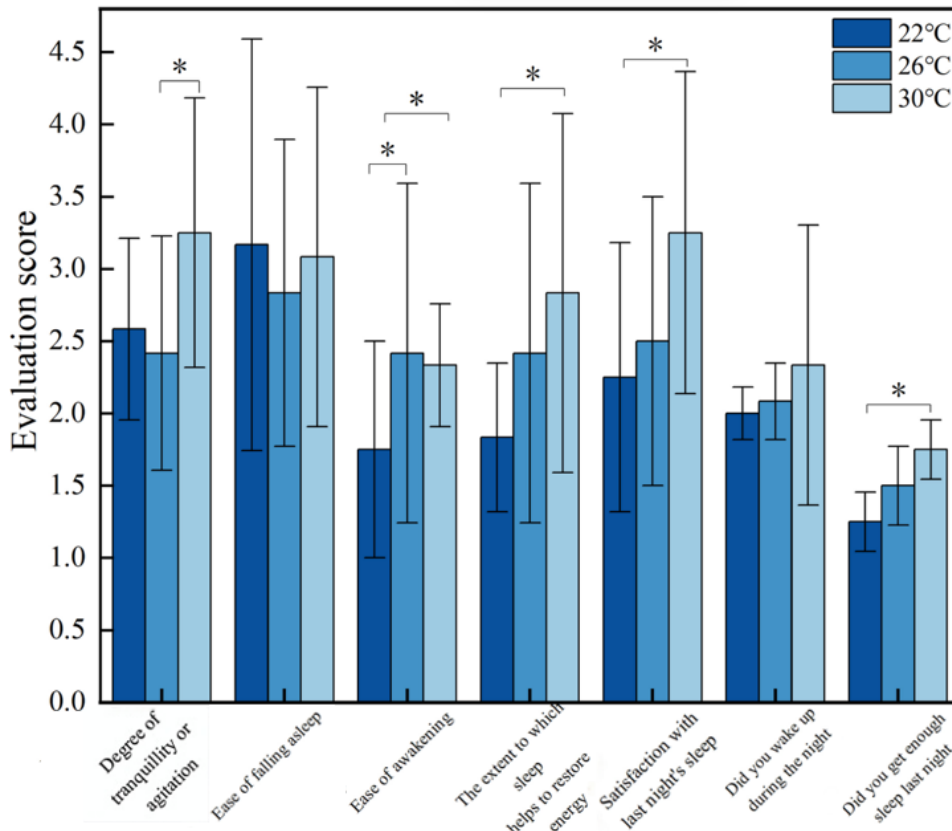


Figure 9. Subjective sleep quality evaluation score

Comparison of the duration of each sleep stage of the subjects is shown in Fig. 10. There was no significant difference between the duration of each stage of the subjects

in the three ambient conditions. At 22°C, the length of core sleep, REM sleep, and deep sleep stages was higher than that of the two ambient temperature conditions, 26°C and 30°C,

and the length of wakefulness was shorter. This is consistent with the results obtained from the subjective sleep questionnaire; deep sleep and core sleep durations were both higher at 30°C than at 26°C, and other sleep stage durations were similar.

Comparative analysis of sleep stages and average skin temperature test results of a certain subject is shown in Figure 11. The results show that there is a good correspondence between the change of sleep stage and the change of average skin temperature. For example, the average skin temperature of the subjects at ①, ②, and ③ in the figure decreases significantly when they enter the deep sleep stage, and the

average skin temperature of the subjects at ③ and ④ increases significantly when they wake up. This is due to the fact that during deep sleep, the body enters a state of deep dormancy and the metabolism slows down, resulting in a decrease in heat production, so the skin temperature decreases; after the subject awakens, the body's metabolism increases and heat production returns, resulting in an increase in the average skin temperature. In addition to this subject, this correspondence between the sleep phase and the average skin temperature during the experiment was also observed in other subjects.

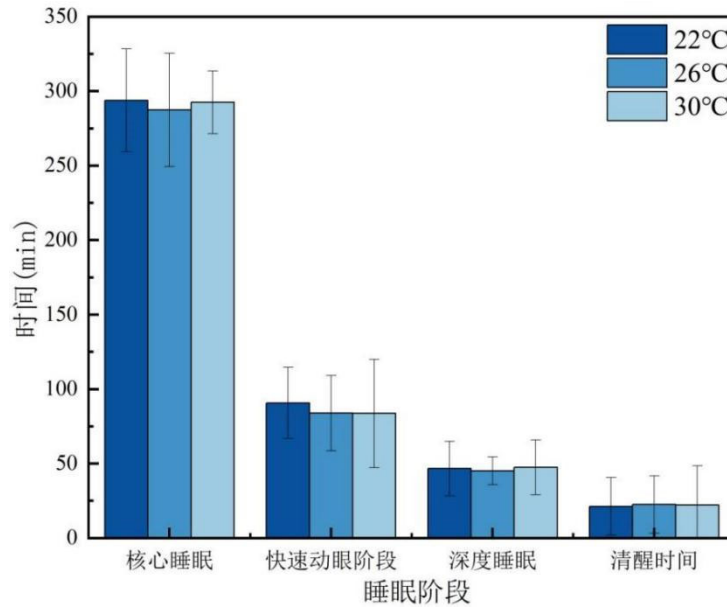


Figure 10. Duration of sleep stages in subjects with different temperature environments

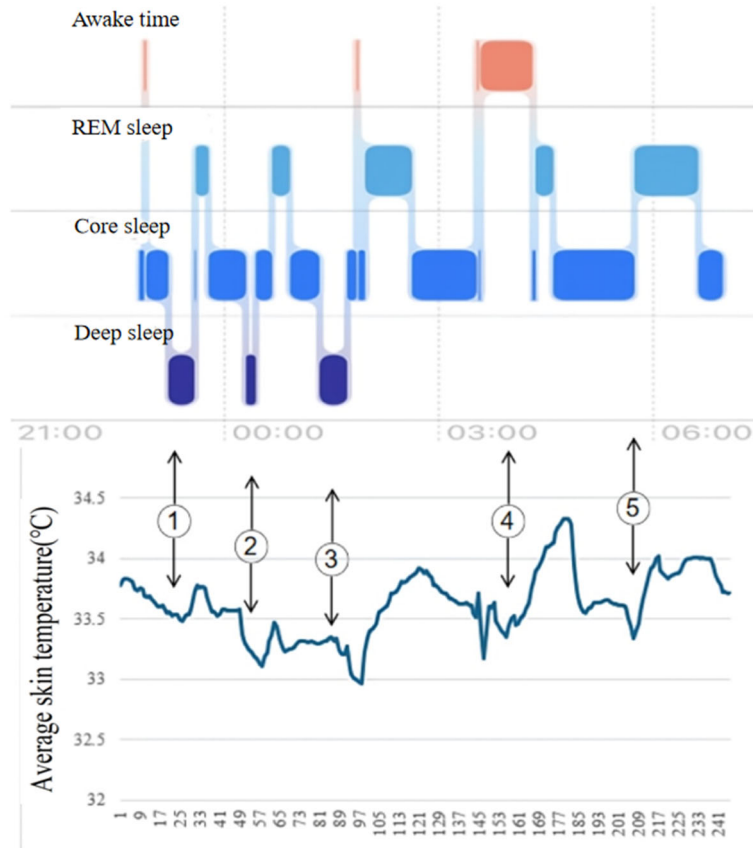


Figure 11. Plot of sleep stages versus mean skin temperature in a subject

3. Discussion

3.1. Effects of different sleep thermal environments on thermal comfort

The results of thermal sensation voting and thermal comfort voting showed that the thermal sensation voting scores increased as the ambient temperature increased, and at the same time, the individual variability increased, and there were significant differences in the thermal sensation of the subjects at different ambient temperatures; in terms of thermal comfort, the results of the voting showed that the subjects felt more comfortable and the latter was better in the 22°C environment and 26°C environment, and uncomfortable in the 30°C environment and the data were highly dispersed, which suggests that This suggests that high temperature significantly reduces people's sleep thermal comfort.

3.2. Effects of different sleep thermal environments on sleep quality

Subjective sleep quality evaluations of subjects in different sleep thermal environments were significantly different. As the thermal environment increased from 22°C to 30°C, the subjective evaluation scores of some questions in the questionnaire increased incrementally, indicating a decrease in sleep quality; whereas some scores showed a trend of low in the middle and high at both ends. Compared with the other two working conditions, subjects scored higher on most of the questionnaires at 26°C. According to the data analysis, it can be seen that the subjective sleep quality of the subjects at 26°C was the highest, followed by 22°C, and the subjective sleep quality of the subjects at 30°C was the worst. The lengths of sleep stages in different temperature environments showed that at 22°C, the lengths of core sleep, rapid eye movement stage, and deep sleep stage were higher than those of other temperature conditions, indicating that the overall sleep time of the subjects was longer at this time. Subjects' deep sleep duration was longer at 30°C, indicating that subjects were more likely to enter deep sleep in hotter environments, although it was difficult to fall asleep. Comparison of sleep stage and average skin temperature showed that there is a correspondence between the sleep stage and the average skin temperature, and it may be possible to monitor the skin temperature to obtain the sleep state.

3.3. Influence of co-sleep thermal environment on thermophysiological parameters

Thermophysiological parameters of the subjects were also significantly affected by the thermal environment of sleep. Regarding the distribution of body surface temperature, overall, the mean skin temperature under the three ambient temperatures had the same trend of change, and as the ambient temperature increased, the mean value of the mean skin temperature also increased; the trend of the mean skin temperature of the subjects under the ambient temperatures of 22°C and 26°C was highly similar; the results of the error analysis showed that, compared with the temperature environments of 22°C and 30°C, the error value was overall smaller and the fluctuation was smoother under the 26°C environment, indicating that the change of the mean skin temperature of the subjects was smaller under this temperature environment. The results of the error analysis show that the overall error value is smaller and the fluctuation

is smoother in the 26°C temperature environment compared to the 22°C and 30°C temperature environments, indicating that the subjects' average skin temperature changes are smaller in this temperature environment. This indicates that the subjects slept smoothly and with high quality under this condition. Analysing the results of other thermophysiological parameters of the subjects, it can be seen that: blood oxygen saturation decreases with the increase of ambient temperature, and the heart rate shows that it first decreases and then increases, and the change of heart rate is related to the quality of sleep, and the lower the heart rate is, the higher the quality of sleep is, so it is possible to get to know the change of temperature through the change of blood oxygen saturation, and the change of the heart rate to know the advantages and disadvantages of the quality of sleep.

4. Conclusions

In this study, a group of university students was selected to investigate the thermophysiological response and sleep quality of human body in colder environment (22°C), neutral environment (26°C), and hotter environment (30°C) through the research method of field experimental test, combined with the subjective questionnaire data and objective physiological parameters, respectively. The following conclusions were obtained:

1) The thermophysiological parameters of the subjects changed significantly with changes in the thermal environment of sleep. The average skin temperature of the subjects during sleep showed the same trend of change in different thermal environments, and its mean value increased significantly with the increase of ambient temperature, and the individual variability of the subjects' skin temperature change was small in the neutral environment, and their sleep was smoother; the blood oxygen saturation decreased with the increase of ambient temperature, and the change of the heart rate was correlated with the quality of the subjects' sleep.

2) Regarding sleep quality, the results of thermal sensation, thermal comfort vote and subjective sleep quality all indicated that the subjects' sleep quality was highest in a neutral environment, next in a colder environment and worst in a hotter environment. By comparing and analysing the changes in the subjects' sleep stages and average skin temperature, it is clear that there is a correspondence between the subjects' sleep stages and the changes in the average skin temperature, and that the sleep status situation can be obtained by monitoring the skin temperature.

This study discusses the thermophysiological responses of the human body under different sleep thermal environments, reveals the link between sleep thermal environment and sleep quality as well as the link between thermophysiological parameters and sleep stages, and provides a theoretical basis for the creation of a comfortable sleep thermal environment.

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