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# Comfortably cool bedroom environment during the initial phase of the sleeping period delays the onset of sleep in summer

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ABSTRACT

Air conditioners are becoming commonly accepted as necessary and conventional in bedroom, but there are very limited researches on thermal comfort of sleeping people. The effects of three air temperature changes were investigated: a constant temperature reference condition (26 °C), a *Fall-Rise* change condition (28 °C–27 °C–26 °C–27 °C–28 °C), and a *Rise-Fall* change condition (25 °C–26 °C–27 °C–28 °C–27 °C–26 °C). Eighteen healthy young people (9 males and 9 females, mean age 23 years) slept in climate chamber and used typical summer covering in the three conditions, with continuous monitoring of multiple physiological parameters. Sleep quality was evaluated subjectively using questionnaires in the morning and objectively by analysis of electroencephalogram (EEG), electrooculogram (EOG) and electromyogram (EMG) signals which were continuously monitored during the sleeping period. Compared with the other two conditions, when the air temperature was kept at a lower but comfortable 25 °C during the initial phase of the sleeping period (*Rise-Fall*), the subjects had colder hands and feet until 90 min after lights off and took longer time to fall asleep, and they reported poorer sleep quality in the morning. In the *Fall-Rise* condition, subjects entered rapid-eye movement sleep later without changing sleep quality or thermal comfort. This study indicates that a comfortably cool environment during the initial phase of the sleeping period delayed the onset of sleep.



## 1. Introduction

People spend about one third of their lives sleeping, and whether sleep can restore the body and its functions depends upon obtaining enough time asleep and good sleep quality. Poor sleep quality impairs cognitive performance in older people [1], and impacts brain function related to reward processing, risk-taking, and cognition in adolescents [2]. Disturbed nocturnal sleep has also been found to be related to various adverse health problems, and increases the risk of death from cardiovascular disease [3]. For research purposes, human sleep quality can be evaluated objectively using the recording of electrooculogram (EOG) for eye movements, electromyogram (EMG) for chin muscle tension, and electroencephalogram (EEG) for brain wave. The measurements of EMG, EOG, and EEG provide the basic information requisite for classifying sleep state and examining sleep processes [4]. The EEG of the nocturnal sleep period is characterized by alternating periods of non-rapid-eye movement (NREM) sleep, subdivided into three (N1 to N3) stages, and rapid-eye movement (REM or R) sleep [5]. Stage N3 sleep is characterized by slow wave activity (brain waves of frequency 0.5 Hz–2 Hz), and is often termed slow wave sleep (SWS) or deep sleep.

The thermal environment may be one of the most important factors that affect human sleep, since thermoregulatory systems have been shown to be strongly linked to the mechanisms regulating sleep [6]. It has been demonstrated that very high or low air temperatures decrease human SWS sleep, and increase the frequency and duration of wakefulness [7,8]. Moreover, in studies that investigated the effects of air temperature on human sleep quality in a constant thermal environment, we observed decrease in sleep quality caused by moderate heat or cold exposure[9–11].

Air conditioners are becoming commonly accepted as necessary and conventional in bedroom in many areas where the summers are hot. Our survey indicated that 90% of 800 families in Shanghai would use air conditioner during sleep in summer [12]. A survey in Hong Kong showed that 68% of 554 respondents leave their air conditioners on throughout their sleep period in summer [13]. A

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national scale survey of summertime temperatures in English dwellings found more than 90% of the dwellings were considered as uncomfortably cool [14]. The issues of thermal comfort in office buildings in different climates have been studied by several researchers and are well documented in the scientific literature [15], but there are very limited researches on thermal environment in bedroom and thermal comfort of sleeping people. Lin and Deng (2008) measured the total insulation of the bedding systems commonly used in the subtropics and established a thermal comfort model determining thermally neutral conditions of sleep environment [16,17]. Pan et al. (2011) numerically studied the microclimate around a sleeping person in a space installed with a displacement ventilation system [18]. Tsuzuki et al. (2015) report effects of seasonal thermal environment on sleep in elderly men [19]. We proposed a bedside personalized ventilation (PV) system and found it could be used as a potential ventilation strategy to improve indoor air quality and thermal comfort in bedroom [20,21]. There are preliminary reports on bed micro climate [22–24], and the relationships between the human body and the bed microenvironment and the ambient environment remain to be studied.

Considering the greatly reduced ability to adjust to the immediate environment while sleeping, it is important to study the application of air-conditioning in bedrooms. In China an energy-conserving algorithm is often applied to the control of many air conditioners without testing its effects on human sleep: the setting temperature of the air conditioner is increased gradually for a period of time and then decreased to its initial value during the night (Rise-Fall change). In contrast, Teramoto et al. (1998) and Wakamura and Tokura (2002) controlled the air temperature as a function of the diurnal change of the internal set-point of core temperature, which falls until the middle of the night and then begins to rise toward the morning (Fall-Rise change) [25,26]. They demonstrated that a gradual decrease of air temperature in the evening and a gradual increase in the morning could accelerate both the nocturnal decrease of core temperature and its morning increase. In the present study, the effects on sleep quality and on physiological responses of these two very different temperature control algorithms were investigated in an attempt to provide a better basis on which to select an appropriate control strategy for air conditioners used in bedroom.

## 2. Methods

### 2.1. Approach

The experiment was carried out (from July to August) in Shanghai in two identical and adjacent sleep chambers equipped with the same type of air conditioner [9]. The subjects were exposed in the chamber for four nights, i.e., one initial “familiarization” night and three consecutive experimental nights. During each exposure in the chamber, in addition to skin temperatures, physiological parameters including EEG, EOG and EMG were continuously monitored to make it possible to quantify sleep quality. The subjects reported sleep quality after getting up and thermal comfort before going to bed and after getting up. An Infrared camera was installed in the chamber to check whether the subjects got up in the night to urinate, thus assisted the scoring of sleep based on the measurement of EEG, EOG and EMG.

The noise level in the room in which subjects slept was 30 dB(A) under all conditions. The background air temperature and relative humidity were recorded by placing a data logger at each of two positions: the middle of the bed head and the bed end, both at a height of 0.4 m above the bed. The data logger (TR-72U, T&D corporation) had a built-in temperature sensor (range: 0–50 °C, accuracy: ±0.5 °C) and a humidity sensor (range: 10–95%, accuracy: ±5%). The air velocity was measured at the same positions with an air flow sensor (UAS1100, Degree Controls Inc., range: 0.15–1.0 m/s, accuracy: ±5% of measured value). The instant values of air temperature, relative humidity and air velocity were record at an interval of 1 min.

### 2.2. Subjects

Eighteen subjects (9 males and 9 females, 21–28 year old, Mean ± SD: 23.0 ± 1.6 years), without sleep disorders gave their informed consent to participate in this study. This background information was obtained by using of Pittsburgh Sleep Quality Index (PSQI) questionnaire, which assesses sleep quality and disturbances over a 1-month time interval [27]. If the candidate had a PSQI global score >5, which is suggestive of a significant sleep disturbance, he/she was excluded. They were exposed to three experimental conditions in a Latin-square design, balanced for order of presentation (Table 1). The subjects were randomly assigned to the three groups. Each night, two subjects from the same group slept in the two chambers, respectively. The subjects were non-smokers and were not taking any medication. The subjects were asked to avoid alcohol, caffeine, and intense physical activity at the daytime during their four day experimental session. Before the beginning of each experiment session their emotion was investigated with the profile of mood states short form (POMS-SF) [28]. The mood states included tension, depression, anger, vigor, fatigue, and confusion, scoring on a 5-point Likert-type scale ranging from 0 (not at all) to 4 (extremely). The total mood disturbance (TMD) was computed by adding the scores for tension, depression, anxiety, fatigue, and confusion, with vigor scores subtracted; the higher the TMD score, the more negative the mood. No significant difference in mood states was observed among the experimental days. The subjects were instructed to wear the same clothing (short-sleeved nightshirt, an estimated insulation value of 0.36 clo) in the experiments. At night they slept on a mattress bed and were covered with a double-layered cotton sheet. The covering material was fixed and the insulation level (including the clothing) was estimated to be 1.64 clo [16]. This study was approved by the relevant ethics committee.

### 2.3. Physiological measurements

EEG (F4-M1, C4-M1, O2-M1, F3-M2, C3-M2, O1-M2), bilateral EOG, and chin EMG were recorded using polysomnographic sleep recording (Somté 32 PSG, Compumedics, Australian). Sleep stages were visually scored every 30 s based on *the 2007 AASM Manual for the Scoring of Sleep and Associated Events* [29]. The calculated sleep statistics included *Total Sleep Time (TST)* - total time scored as sleep (in minutes), *Sleep Efficiency (SE)* – percentage of time in bed actually spent sleeping (%), *Sleep Onset Latency (SOL)* - the time between lights off and the first occurrence of stage N1 sleep (the start of sleep) (in minutes), Latency to (the time between light off and the first occurrence of) stage N2, N3 and R (in minutes), Total duration of stage N1, N2, N3 and R stage (in minutes). Higher *sleep efficiency*, higher duration of N3 stage, and shorter *sleep onset*

**Table 1**
Balanced Latin-square design of this experiment.

| Subjects | Exposure order | | |
|---|---|---|---|
| | 1st night | 2nd night | 3rd night |
| Group 1 (6 subjects) | C1 Constant | C2 Rise-Fall | C3 Fall-Rise |
| Group 2 (6 subjects) | C2 Rise-Fall | C3 Fall-Rise | C1 Constant |
| Group 3 (6 subjects) | C3 Fall-Rise | C1 Constant | C2 Rise-Fall |

*latency* indicate higher sleep quality.

Skin temperatures at seven sites (forehead, chest, arm, hand, thigh, leg, and foot) were measured at 1-min intervals using PyroButtons (Pyrobutton-L; Dallas, TX, USA) with an accuracy of ±0.2 °C from −40 °C to +85 °C and a 0.0625 °C resolution. The bottom side, with a protruding edge, of the PyroButton was fixed onto the skin with adhesive tape. The validity of using such wireless sensors to measure skin temperature has been reported in previous studies [30,31]. Mean skin temperature (MST) was calculated as the mean of local skin temperatures multiplied by their respective weight factors [32]. The proximal and distal skin temperatures were calculated as follows [32]: (1) For proximal skin temperature: [forehead × 0.115] + [chest × 0.574] + [thigh × 0.311] and (2) for distal skin temperature: [arm × 0.3590] + [hand × 0.1282] + [leg × 0.3333] + [foot × 0.1795]. The distal-to-proximal skin temperature gradient (DPG) was calculated as the difference: [distal skin temperatures] minus [proximal skin temperatures] [33]. Vasodilation, by increasing the skin temperature of the hands and feet, thus decreases the difference between proximal and distal values and decreases the negative DPG value.

### 2.4. Subjective questionnaires

The subjects reported their subjective perception of sleep quality on seven numerical scales. These assessed the *calmness of sleep*, *ease of falling asleep*, *ease of awakening*, *freshness after awakening*, *satisfaction with sleep*, *night-time awakening frequency* and *sufficient sleep* (Table 2) [34]. Higher score of the former 5 items and lower score of the '*night-time awakening frequency*' indicate higher sleep quality. A 7-point scale (-3-cold, -2-cool, -1-slightly cool, 0-neutral, 1-slightly warm, 2-warm, 3-hot) was used to report thermal sensation. Overall thermal comfort was reported on a 6-point scale (-3-very uncomfortable, -2-uncomfortable, -1-slightly uncomfortable, 1-slightly comfortable, 2-comfortable, 3-very comfortable).

### 2.5. Experimental conditions and procedure

Three thermal conditions were established by changing the set temperature of air conditioner between four closely-controlled levels: 25 °C, 26 °C, 27 °C, and 28 °C. In our former study, 26 °C was shown to be the neutral temperature for sleeping with a total (clothing plus bedcover) insulation of 1.64 clo. The temperature of 25 °C was established to study the effect of a comfortably cool environment on sleep onset, considering that people usually set the temperature of air conditioner based on their thermal sensation before going to sleep, while still awake, so their thermal comfort temperature is lower than it is for sleep [9,11]. The temperature of 28 °C was expected to be the upper limit temperature for establishment of a comfortably warm environment for sleep, and 27 °C was a transitional level between 26 °C and 28 °C. Fig. 1A shows the detailed changes of set-point that took place in the two changing-temperature conditions and the *C1-Constant-temperature* condition that served as the baseline condition. Fig. 1B shows that the measured values of air temperature lagged only slightly behind the changes in set point. In the initial "familiarization" night, air temperature was 26 °C throughout.

The same schedule was applied to each condition. After arriving at the chamber, the subjects rested there for 30 min, wearing short-sleeved nightshirts (the estimated clothing value being 0.5 clo). After this adaptation period, the thermal comfort evaluation, which lasted approximately 5 min, was performed. Next the physiological parameters probes were applied; this process lasted 30 min. Then the lights were turned off and 8 h sleeping time started. The physiological parameters were continuously measured throughout the night until the subjects were woken up prompt in the next

**Table 2**
Items for subjective sleep quality assessment.

| Questions | Response alternatives | Score |
|---|---|---|
| 1. How was your sleep last night? (*calmness of sleep*) | Very calm | 5 |
| | Fairly calm | 4 |
| | Neither calm nor restless | 3 |
| | Quite restless | 2 |
| | Very restless | 1 |
| 2. How easy was it to fall asleep last night? (*ease of falling asleep*) | Very easy | 5 |
| | Fairly easy | 4 |
| | Neither easy nor difficult | 3 |
| | Quite difficult | 2 |
| | Very difficult | 1 |
| 3. How easy was it to wake up this morning? (*ease of awakening*) | Very easy | 5 |
| | Fairly easy | 4 |
| | Neither easy nor difficult | 3 |
| | Quite difficult | 2 |
| | Very difficult | 1 |
| 4. Did you feel refreshed after waking? (*freshness after awakening*) | Fully | 5 |
| | Fairly | 4 |
| | Moderately | 3 |
| | Not much | 2 |
| | Not at all | 1 |
| 5. Did you satisfied with your last night's sleep? (*satisfaction about sleep*) | Fully | 5 |
| | Fairly | 4 |
| | Moderately | 3 |
| | Not much | 2 |
| | Not at all | 1 |
| 6. Did you wake up during the night? (*night-time awakening frequency*) | Never | 1 |
| | 1 to 2 times | 2 |
| | 3 to 4 times | 3 |
| | Often | 4 |
| 7. Did you get enough sleep? (*sufficient sleep*) | Yes | – |
| | No | – |

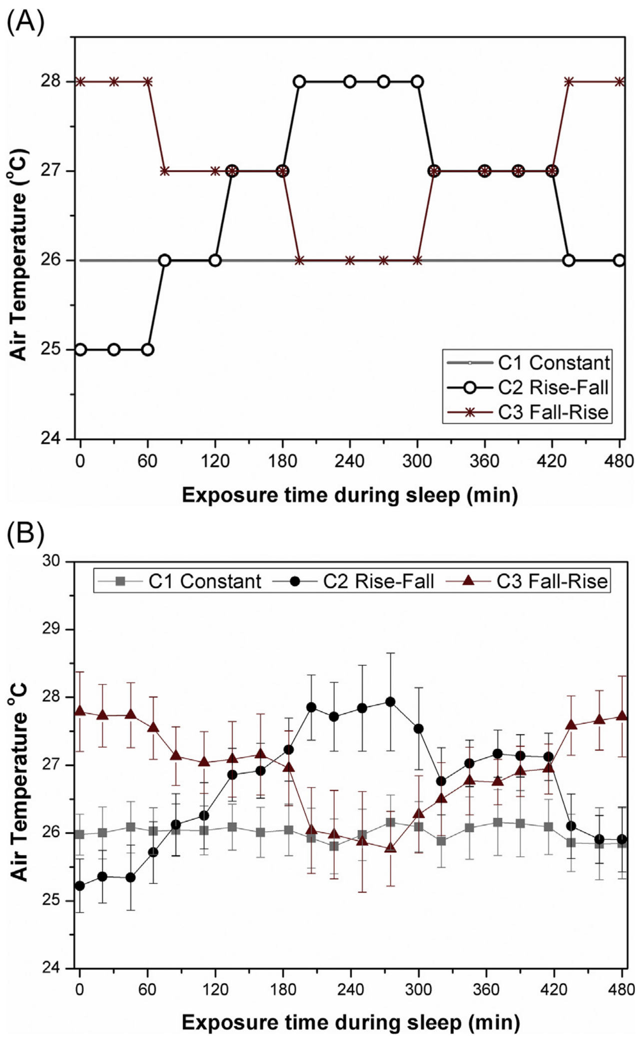


**Fig. 1.** (A) Schematic changes and (B) measured changes (mean ± STD) in air temperature during sleep.

morning. After getting up, the subjects completed questionnaires regarding sleep quality and thermal comfort, which took approximately 10 min. In addition to their perception of thermal comfort at that moment, they were also asked to recall their thermal sensation during the previous night.

### 2.6. Statistical analysis

The measured data were first tested for normality using Shapiro-Wilk's W test. Normally distributed data were subjected to analysis of variance in a repeated measures design and a Paired Samples T test. Not-normally distributed data were analyzed using Friedman's analysis of variance and Wilcoxon Signed-Ranks test. The significance level was set to be 0.05 ($P \leq 0.05$). Effect size (*ES*), the difference between the true value and the value specified by the null hypothesis, was derived as an indicator of whether the difference was of practical importance [35].

## 3. Results

### 3.1. Physical environment

As shown in Fig. 1B, the measured air temperature during the three experimental nights did not deviate from the intended levels. The value of mean radiant temperature was almost the same as air temperature. Low air velocity (<0.2 m/s) was kept around the bed during the sleeping period. The relative humidity varied within a narrow range of 45–60%.

### 3.2. Thermal comfort

Different levels of thermal sensation were reported in the three conditions ($P < 0.01$, $ES = 0.75$). The subjects felt warmer in the *C3-Fall-Rise* condition than in the other two conditions before going to bed and after getting up; they also felt warmer in the *C1-Constant* condition than in the *C2-Rise-Fall* condition before going to bed. After getting up they recalled that they felt warmer during sleep in the *C3-Fall-Rise* than in the *C1-Constant* condition (Fig. 2). In terms of the thermal sensation reported for the three time periods, a significant difference was found in the *C1-Constant* condition: the subjects felt cooler during and after sleep compared with before sleep (Fig. 2, Table 3).

A significant difference in overall thermal comfort between the three conditions was only found before going to bed ($P < 0.01$, $ES = 0.71$); the subjects considered the environment to be less comfortable than in either of the other two conditions (but still to be comfortable) in the *C3-Fall-Rise* condition (Fig. 3). Table 3 shows the multiple comparisons of thermal comfort assessed in the three time periods. They reported lower thermal comfort during and after sleep than before sleep in the *C1-Constant* and *C2-Rise-Fall* condition. Thermal sensation and overall thermal comfort assessments indicate that in this experiment the air temperatures changed within the thermal comfort zone.

### 3.3. Sleep quality

The subjects reported lower levels of their '*Calmness of sleep*' and '*Satisfaction with sleep*' and higher '*night-time awakening frequency*' in the *C2-Rise-Fall* condition compared with the other two conditions (Fig. 4). Fewer subjects reported that they 'got enough sleep' in the *C2-Rise-Fall* (percentage of 62.5%) and the *C1-Constant* (68.75%) than in the *C3-Fall-Rise* (81.25%) ($P < 0.10$, $ES = 0.35$).

The polysomnographic data shows that the subjects took longer to fall asleep in the *C2-Rise-Fall* condition than in either of the other two conditions (Fig. 5A). Fig. 5B shows that they entered stage R sleep later in the *C3-Fall-Rise* condition than in either of the other two conditions. No significant difference between the three

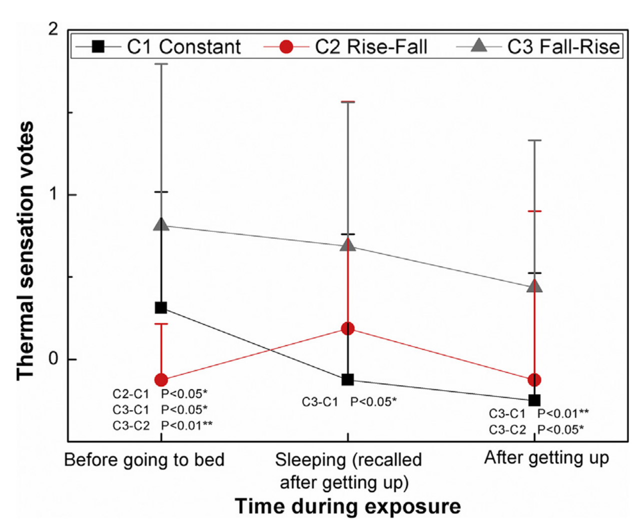


**Fig. 2.** Thermal sensation assessed in the three temperature conditions (Error bars represent the standard deviation of the mean (STD)).

**Table 3**
Multiple comparisons in thermal sensation and overall thermal comfort.

| Time effects | | Multiple comparisons[a] | | |
|---|---|---|---|---|
| | | Before-Sleeping | Before-After | Sleeping-After |
| Thermal sensation | *C1–Constant* | <0.05* | <0.05* | 0.32 |
| | *C2–Rise-Fall* | 0.40 | 0.89 | 0.20 |
| | *C3–Fall-Rise* | 0.73 | 0.32 | 0.16 |
| Overall thermal comfort | *C1–Constant* | <0.01** | <0.05* | <0.05* |
| | *C2–Rise-Fall* | <0.01** | 0.15 | 0.26 |
| | *C3–Fall-Rise* | 0.55 | 0.28 | <0.05* |

*$P < 0.05$, **$P < 0.01$.
[a] Before-before going to bed; Sleeping-Sleeping (recalled after getting up); After-after getting up.

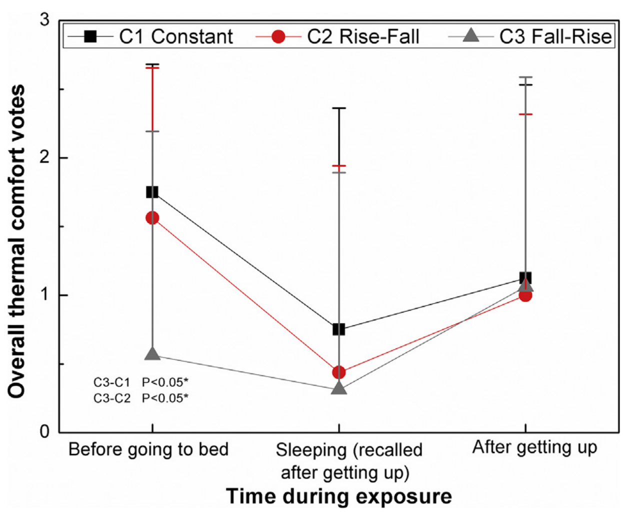


**Fig. 3.** Thermal comfort assessed in the three temperature conditions (Error bars represent the standard deviation of the mean (STD)).

subjects throughout the night: similar variation patterns in MST were observed under all three conditions. The skin temperature increased rapidly after lights off and then decreased gradually to a minimum, although the decrease of skin temperature was greatly suppressed by the increasing air temperature in the *C2-Rise-Fall* condition, while this decrease in skin temperature was accelerated by the decreasing air temperature in the *C3-Fall-Rise* condition. The skin temperature was significantly higher towards the end of the *C3-Fall-Rise* condition than it was in the *C1-Constant* condition.

Fig. 7 demonstrates the temporal changes of the distal-to-proximal skin temperature gradients (DPG) throughout the night. Significant differences were found during the first 90 min after lights off: the most negative DPG was observed in the *C2-Rise-Fall* condition.

## 4. Discussion

This study investigated the effects of slow bedroom air temperature changes that are produced by three common ways of controlling air conditioner. Thermal comfort and sleep quality were monitored during whole night exposures under each of these

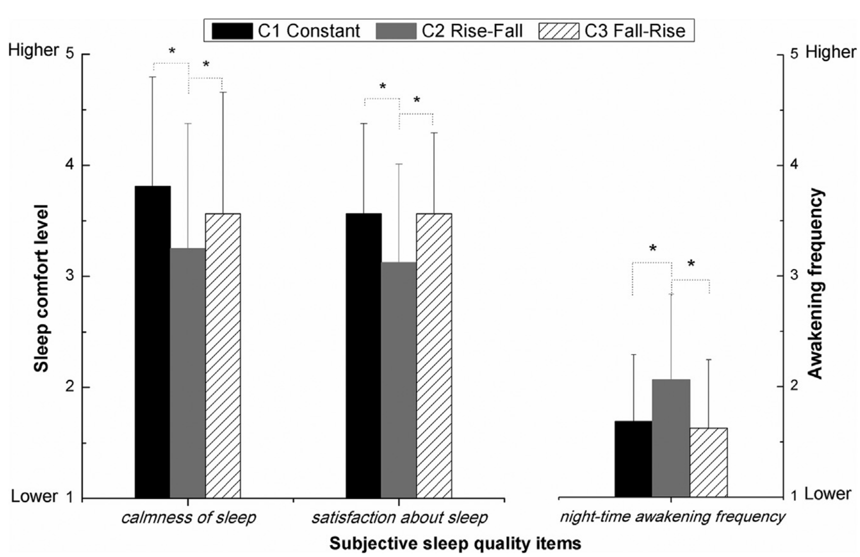


**Fig. 4.** Difference in subjective sleep quality assessed in the three temperature conditions (Error bars represent the standard deviation of the mean (STD)).

temperature conditions was found in other sleep quality parameters (Table 4).

### 3.4. Skin temperature

Fig. 6 shows the temporal changes in averaged MST of all

conditions. According to the thermal sensation votes assessed before sleep, the subjects unsurprisingly felt cooler at 25 °C (before *C2-Rise-Fall*) than at 26 °C (before *C1-Constant*) or at 28 °C (before *C3-Fall-Rise*). Considering these thermal sensation votes together with the sleep onset latency results shown in Fig. 5A, it is clear that compared with a comfortably warm environment, a comfortably

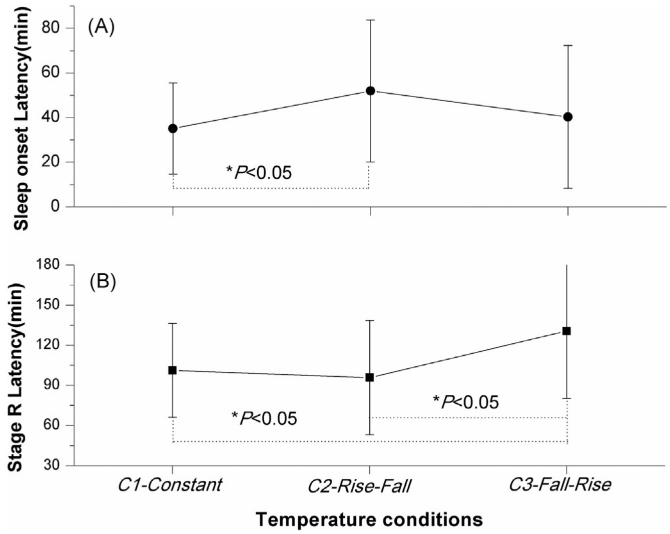


**Fig. 5.** (A) Sleep onset latency increased in the C2–Rise-Fall condition and (B) Stage R latency increased in the C3-Rise-Fall condition (Error bars represent the standard deviation of the mean (STD)).

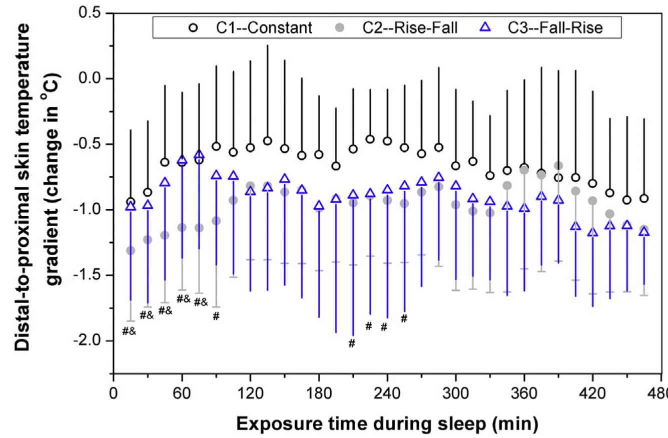


**Fig. 7.** Temporal changes of distal-to-proximal skin temperature gradients (Error bars represent the standard deviation of the mean (STD)). # indicates a significant difference between C1 and C2, * between C1 and C3, & between C2 and C3.

**Table 4**
Sleep quality parameters measured with PSG in the three temperature conditions.

| Parameters | Cycles | | | | |
|---|---|---|---|---|---|
| | C1-constant | C2-rise-fall | C3-fall-rise | Sig. | Effect size |
| Total sleep time, minute | 395.0 ± 24.5 | 391.2 ± 32.7 | 393.5 ± 36.5 | 0.89 | 0.10 |
| Sleep efficiency, % | 85.3 ± 5.4 | 84.3 ± 7.2 | 84.8 ± 7.2 | 0.91 | 0.09 |
| Total duration, minute | | | | | |
| N1 | 27.7 ± 11.0 | 27.1 ± 15.0 | 32.9 ± 20.6 | 0.34 | 0.34 |
| N2 | 174.3 ± 26.6 | 167.1 ± 29.4 | 171.4 ± 31.9 | 0.77 | 0.16 |
| N3 | 121.8 ± 24.8 | 123.0 ± 37.2 | 123.9 ± 24.5 | 0.90 | 0.11 |
| R | 71.2 ± 11.1 | 73.9 ± 20.4 | 65.2 ± 10.5 | 0.32 | 0.35 |
| Percentage of sleep time, % | | | | | |
| N1 | 7.1 ± 2. | 7.0 ± 3.8 | 8.4 ± 5.0 | 0.35 | 0.33 |
| N2 | 44.0 ± 5.27 | 42.7 ± 6.6 | 43.4 ± 5.9 | 0.85 | 0.13 |
| N3 | 30.9 ± 6.2 | 31.4 ± 8.8 | 31.6 ± 5.9 | 0.86 | 0.12 |
| R | 18.0 ± 2.7 | 18.8 ± 4.7 | 16.6 ± 2.7 | 0.26 | 0.38 |

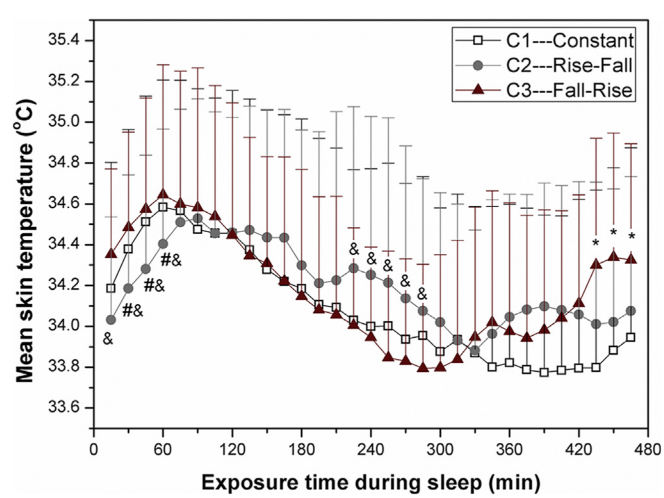


**Fig. 6.** Temporal changes of mean skin temperature gradients (Error bars represent the standard deviation of the mean (STD)). # refers to significant difference between C1 and C2, * indicates a significant difference between C1 and C3, & between C2 and C3.

cool environment tended to impede the onset of sleep. This undesirable effect is likely to be due to the decreased vasodilation that was observed in the cooler condition (Fig. 7). Kräuchi et al. (1999) showed that the degree of dilation of blood vessels in the skin of the hands and feet, which increases heat loss at these extremities, is the best physiological predictor for the rapid onset of sleep [33]. The greater the vasodilation in the late evening, the shorter was the time taken to fall asleep [33]. Since reduced skin blood flow is the elementary thermoregulatory response of the body to a cool environment, our results suggest that the bedroom should be kept comfortably warm in the late evening to facilitate the initiation of sleep. It is difficult for the subjects to precisely report the onset of sleep, as studies have found that a change in EEG pattern is not always associated with a person's perception of sleep [36]. This may explain why no significant difference was observed in subjective report on “ease of falling asleep”.

The subjects reported poorer sleep quality (Fig. 4) and took longer to fall asleep in the *C2-Rise-Fall* condition than in the other two conditions (Fig. 5A). The results may suggest that such a gradual increase and then a gradual decrease in air temperature may have negative effects on sleep quality. The reason is likely to be that the air temperature change in this condition was in opposition to physiological requirements, since in humans the core temperature falls until the middle of the night and then begins to rise towards the morning. However, the reported poorer sleep quality may be solely due to the delayed onset of sleep, which was caused by the initially cooler environment. Further studies are needed to valid the effects of this *Rise-Fall* shaped temperature change on sleep. When the air temperature was changed so as to follow the core temperature change (the *C3-Fall-Rise* condition), compared to the *C1-Constant* condition, the onset of R sleep was delayed (Fig. 5B) without changing sleep quality parameters (Fig. 4, Table 4). By using slow air temperature transients (±3 °C) around 29 °C (thermal neutrality when sleeping nude), Dewasmes et al. (1996) were able to advance the minimum core temperature and the peak of R sleep [37]. Teramoto et al. (1998) found that a temperature change of ±1.5 °C had a profound influence on core body temperature during the night [25]. They also showed that a gradual decrease of air temperature in the evening and a gradual increase in the morning could accelerate the nocturnal fall of core temperature and its morning rise, and this was confirmed by Wakamura and Tokura (2002) [26]. Core body temperature was not measured in the present experiment, in order to avoid any sleep disturbance that might be caused by the presence of rectal probes. There are still no convenient and noninvasive methods for the measurement of human core temperature over a long period. Such methods will have to be developed and should be used in future studies.

In the present study, compared with the *C1-Constant* condition, subjects reported almost the same sleep quality (Fig. 4) and thermal comfort during sleep (Fig. 3), and their sleep quality parameters (Table 4) were found to be very similar in the *C3-Fall-Rise* condition, while the skin temperature was higher towards the end of the *C3-Fall-Rise* condition. These results indicate that the indoor air temperature could be slightly raised during the later sleeping period, as this increase in MST in the morning hours is likely to reduce the frequency of waking up feeling cold, and this is supported by the results of a survey in Hong Kong in summertime, which found that up to a quarter of the respondents reported waking up because of low indoor air temperature when their bedroom air conditioners were in operation [13]. It should be noted that it is difficult for the subjects to accurately assess their thermal comfort during sleep. Due to the lack of thermal comfort information, the causal relationship between thermal comfort and sleep quality cannot be developed yet. Concurrently measurement of physiological parameters such as skin temperature and heart rate variability, which were found to be related to thermal comfort in waking people [38,39], along with sleep to monitor thermal comfort state are needed in future studies.

## 5. Conclusions

- The subjects took longer time to fall sleep in the *C2-Rise-Fall* condition than in either of the other two conditions. The lower initial air temperature in the *C2* conditions led to vasoconstriction, to reduce heat loss, and this has been shown in previous research to increase sleep latency. To facilitate the initiation of sleep, the air temperature in bedroom thus should not be too low during the beginning part of the sleeping period.
- Subjects reported poorer sleep quality in the *C2-Rise-Fall* condition than in either of the other two conditions. The slow increase in air temperature after sleep onset in this condition opposed the naturally occurring decrease in core temperature, but further research is required to show that this was the reason for the observed effect.
- Compared with *C1-Constant* condition, the subjects in the *C3-Fall-Rise* condition reported almost the same sleep quality and overall thermal comfort during sleep. This result indicates that the bedroom air temperature could be slightly elevated during the later sleeping period.

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