



A Preliminary Study of the Effect of Mattress Temperature on the Subjective and Objective Sleep Quality of Healthy Young Adults

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Objective: We evaluated the effects of microclimate temperature on the subjective and objective sleep quality of healthy young adults. For this purpose, we maintained a constant ambient temperature and manipulated the mattress temperature to change the microclimate.

Methods: We enrolled 34 healthy young adults (12 males and 22 females; mean age: 24.06±2.70 years). Data from 26 individuals were analyzed (8 males and 18 females; mean age: 23.46±2.40 years). Nocturnal polysomnography (nPSG) was performed and self-reported questionnaires were completed at an ambient temperature of 27°C and mattress temperature of 28°C, 30°C, or 32°C. **Results:** The subjective sleep satisfaction was lower at a mattress temperature of 32°C than at 28°C. The subjective sleep latency was longer at 32°C than at 30°C. The number of respondents that selected sleep environment (including temperature) as the cause of sleep dissatisfaction was greater at higher temperatures. Participants felt that the mattress temperature was the least cool when they woke up at 32° than 30°C. Furthermore, they reported that the sleep latency at 32°C was longer than the other temperatures compared to usual sleep, and that they had more frequent awakenings at 32°C than at 28°C. The nPSG results showed that the proportion of rapid eye movement (REM) sleep was lower at 28°C than at 30°C. **Conclusion:** A high microclimate temperature caused by a high mattress temperature was associated with poor subjective sleep quality. Mattress temperature was also related to the objective proportion of REM sleep; however, the results are inconsistent with previous findings. Additional large-scale studies that evaluate a wider temperature range are required.

Keywords: Sleep; Environment; Microclimate; Temperature; Sleep quality

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INTRODUCTION

Sleep is essential for the healthy life of animals, including humans. A sufficient quantity and good quality of sleep promote mental and physical health and support recovery from fatigue. Several studies have evaluated the effects of sleep environment (e.g., temperature, humidity, airflow, lighting, and noise) on sleep [1-5].

The thermal environment affects sleep by influencing skin temperature, which changes continuously during sleep stages (i.e., N1-3 and rapid eye movement [REM]) [6]. Thermoneutrality refers to the temperature range at which heat production through minimal metabolism is balanced by environmental heat loss [7].

Extremes of temperatures outside this range and sudden temperature changes promote thermoregulation, resulting in decreased sleep efficiency and poor sleep quality [8-11]. Therefore, it is necessary to determine the ambient temperature (T_a) and microclimate temperature (T_m) that maintain the skin in a thermoneutral state during sleep to achieve good-quality sleep.

Previous studies have reported that the appropriate sleep T_a (i.e., air temperature of the sleep environment) is >10°C [6]. A review of studies of sleep environmental conditions found that the optimal indoor temperature is 17°C–28°C [12]. A previous study revealed higher subjective sleep quality at 26°C than at 23°C or 30°C [13]. Another study showed improved sleep efficiency by maintaining the room temperature at 26°C–28°C during the ear-

ly stage of sleep and at 28°C during the late stage [14].

Most studies have focused on T_a , but the T_m inside the bed, which is closer to the body, has not been adequately evaluated. Several studies have suggested that T_m has a greater effect on sleep comfort than T_a [6,15,16]. Rohles and Munson [17] revealed that room temperatures of 10°C, 21.1°C, and 32.2°C did not significantly affect the rate of sleep stages. Furthermore, a stable and adequate T_m contributes to sleep quality [18–21].

Good sleep quality requires an appropriate T_m range. The bed T_m should generally be higher than the T_a as it may induce peripheral vasodilation and promote sleep onset and maintenance [21,22]. Previous studies have suggested that a T_m of almost 30°C is the most appropriate [9,23,24]. Similarly, other studies have reported an appropriate T_m of 28°C–31°C [25,26]. One study reported that a T_m of 30°C–32.5°C, which is slightly higher than the aforementioned range, is optimal [27]. Some studies have also reported that the appropriate upper range of the T_m is 35°C [17,22].

Previous studies have identified thermoneutral T_a and T_m values. However, only a few studies have evaluated the effects of the T_a and T_m on sleep, and most of these studies evaluated the optimal ranges of these values [6,21,24]. To the best of our knowledge, no previous study has directly evaluated the differences in sleep quality between different temperatures within the appropriate T_m range. Additionally, most studies have used objective tools to measure sleep quality; only a few have used subjective questionnaires related to T_m [9].

We investigated the effects of different T_m conditions on sleep quality in the same ambient environment. Because humans actively alter the T_m to regulate skin temperature through behaviors such as removing covers while sleeping [22], we minimized the influence of these thermoregulatory behaviors by maintaining a constant mattress temperature throughout the night. The study participants slept at the three mattress temperatures. We observed the changes in subjective sleep quality using self-reported questionnaires as well as objective sleep quality through nocturnal polysomnography (nPSG). We hypothesized that there would be a significant difference in the sleep parameters according to the mattress temperature, and that sleep quality would decrease particularly at 32°C, which was the highest temperature used in this experiment.

METHODS

Participants

We recruited healthy young adults aged 20–30 years who did not have sleep problems or insomnia to control for the effect of age on sleep. We excluded participants who were pregnant or lactating; had previous or current serious internal and/or external medical conditions; were taking psychiatric medications (e.g., sleeping pills); had severe snoring, leg numbness, or abnormal behavior during sleep within the prior 3 months; had psychiatric disorders; or worked in jobs associated with irregular sleep-wake cycles, such as shift work.

In total, 12 males (mean age: 23.64±1.80 years; range: 22–27 years) and 22 females (mean age: 24.26±3.05 years; range: 20–29 years) were invited to participate in the study through advertisements. We excluded six participants who did not complete the study procedures and two who had erroneous nPSG recordings. Finally, data from 8 males (mean age: 23.88±2.03 years; range: 22–27 years) and 18 females (mean age: 23.22±2.51 years; range: 20–29 years) were analyzed. This study was approved by the Institutional Review Board of Seoul National University Hospital (IRB no. 2107-218-1240). The study procedures were conducted after obtaining written informed consent from the participants.

Assessments

Study conditions

Considering previous results, the T_a was maintained at 27°C throughout the experiment [13,14], and the mattress temperature was adjusted to 28°C (A), 30°C (B), or 32°C (C) with a difference of ±2°C based on 30°C [9,23,24]. The order of mattress temperature resulted in six combinations (i.e., ABC, ACB, BAC, BCA, CAB, and CBA). Participants were randomly assigned to each combination and blinded to the randomization. To minimize a carryover effect, we selected intervals of 1 week ± 3 days (4–10 days) between the tests. nPSG was conducted from the end of September to the beginning of March of the following year.

We instructed participants to continue their daily lives during the study period. A thin cotton pad was laid on the mattress, and a light cotton cover was provided. Participants slept in their regular sleepwear during nPSG. The temperature control mattress was provided by Kyungdong Navien Co., Ltd. (Seoul, Korea).

Subjective sleep parameters

Self-reported sleep parameters were measured once at the baseline interview and three times after nPSG at each mattress temperature. The pre-nPSG baseline questionnaires included the Pittsburgh Sleep Quality Index (PSQI), Epworth Sleepiness Scale, Morningness-Eveningness Questionnaire (MEQ), Dysfunctional Beliefs and Attitudes about Sleep Scale (DBAS), Beck's Anxiety Inventory (BAI), Beck's Depression Inventory (BDI), and several questions about the participants' usual sleep patterns.

The PSQI is a highly reliable tool to measure overall sleep quality and sleep-related symptoms over the past month. It has 19 items and its scores range from 0 to 21. Higher total scores indicate lower subjective sleep quality, and a score of ≥6 indicates poor sleep quality [28]. The Epworth sleepiness scale is used to evaluate daytime sleepiness in daily life; a total score of ≥10 indicates significant daytime sleepiness [29]. The DBAS measures unrealistic expectations and false beliefs about sleep. Higher scores correlate with greater dysfunctional belief regarding sleep [30]. The MEQ evaluates the circadian rhythm and its score is divided into “definitely morning type,” “moderately morning type,” “intermediate type,” “moderately evening type,” and “definitely evening type” [31]. The BAI and BDI are used to measure anxiety and de-

pression, respectively [32,33]. Additionally, usual sleep satisfaction, reasons for (dis)satisfaction, and subjectively assessed sleep parameters, such as total sleep time (TST), sleep latency (SL), and number of awakenings (NOA), were recorded.

The post-nPSG questionnaires included self-report questions about the relative SL, perception of mattress temperature, and several indicators of sleep quality (e.g., depth and quantity of sleep, frequency of awakenings and dreams, and sleep comfort) in addition to some of the pre-nPSG items (e.g., sleep satisfaction, reasons for [dis]satisfaction, TST, SL, and NOA). To assess TST, SL, and NOA on the post-nPSG questionnaires, both multiple choice and subjective responses were recorded.

Objective sleep parameters

nPSG is an objective method that is widely used to evaluate the factors that determine sleep quality, such as TST, SL, sleep efficiency, wake after sleep onset, and sleep stages [34]. nPSG was performed under the three mattress temperature conditions.

nPSG was performed to evaluate objective sleep parameters. We used Profusion software (ver. 3.4; Compumedics, Victoria, Australia) to analyze the nPSG recordings. During sleep, electroencephalograms, electrocardiograms, electrooculograms, chin and limb electromyograms, snoring sounds, oral and nasal air-flow, chest and abdominal movements, body position, and arterial oxygen saturation were continuously measured. Sleep stages and events were scored and sleep parameters were calculated using American Academy of Sleep Medicine criteria [35].

Statistical analysis

Data were analyzed using SPSS software (version 25.0; IBM Corp., Armonk, NY, USA). We performed paired t-tests to determine whether there were significant differences between participants' usual and experimental sleep measurements. Repeated measures analysis of variance (ANOVA) showed significant differences in sleep parameters according to each mattress temperature. Fisher's least significant difference (LSD) test was used for post hoc analysis. Statistical significance was set at $p < 0.05$.

RESULTS

Baseline assessments

Table 1 presents the demographic characteristics and pre-nPSG baseline information of the participants. The mean PSQI score was 4.19 ± 1.41 , which is less than 6 (i.e., the standard for poor sleep). The average ESS score was 4.73 ± 2.72 . The average MEQ score was 40.63 ± 8.59 , and the DBAS averaged 121.08 ± 41.40 . The mean BAI and BDI scores were 2.50 ± 3.84 and 4.12 ± 6.09 , respectively.

Comparisons of subjective sleep parameters between different mattress temperatures

Paired t-tests were conducted to compare participants' usual sleep to experimental sleep at each mattress temperature. No significant difference was found in sleep satisfaction, while there

Table 1. Demographic characteristics and baseline information

Characteristic	Male (n=8)	Female (n=18)	Total (n=26)
Age (yr)	23.88±2.03	23.22±2.51	23.46±2.40
Weight (kg)	71.45±14.00	54.99±8.89	60.05±12.98
Height (cm)	173.84±6.95	162.28±4.59	165.83±7.58
BMI	23.54±3.74	20.82±2.86	21.66±3.33
PSQI	4.00±1.41	4.28±1.45	4.19±1.41
ESS	5.38±3.07	4.44±2.59	4.73±2.72
MEQ	42.69±10.59	39.72±7.71	40.63±8.59
DBAS	127.00±35.53	118.44±44.47	121.08±41.40
BAI	1.75±1.83	2.83±4.46	2.50±3.84
BDI	3.75±2.66	4.50±7.66	4.12±6.09
Sleep satisfaction	2.25±0.46	2.61±0.92	2.50±0.81
sTST	3.75±0.71	3.44±1.04	3.54±0.95
sSL	1.38±0.52	1.78±0.55	1.65±0.56
sNOA	1.50±0.53	1.56±0.98	1.54±0.86

Data are presented as mean±standard deviation. BMI, body mass index; PSQI, Pittsburgh Sleep Quality Index; ESS, Epworth Sleepiness Scale; MEQ, Morningness-Eveningness Questionnaire; DBAS, Dysfunctional Beliefs and Attitudes about Sleep Scale; BAI, Beck's Anxiety Inventory; BDI, Beck's Depression Inventory; sTST, subjective total sleep time; sSL, subjective sleep latency; sNOA, subjective number of awakenings

were significant differences in subjective TST, SL, and NOA (sTST, sSL, and sNOA) between pre- and post-nPSG under all conditions (sTST—28°C: $t=2.44$, $p < 0.05$; 30°C: $t=2.67$, $p < 0.05$; 32°C: $t=3.71$, $p < 0.01$; sSL—28°C: $t=-2.24$, $p < 0.05$; 30°C: $t=-2.39$, $p < 0.05$; 32°C: $t=-4.54$, $p < 0.001$; sNOA—28°C: $t=-9.87$, $p < 0.001$; 30°C: $t=-8.42$, $p < 0.001$; 32°C: $t=-14.15$, $p < 0.001$). Taken together, the participants appeared to sleep less, took longer to fall asleep, and woke up more frequently during the experiment compared to their usual sleep, despite similar sleep satisfaction levels (Table 2).

Repeated measures ANOVA was performed to identify whether there were significant differences among post-nPSG subjective parameters under each mattress condition (Table 3). The results revealed that the differences in sleep satisfaction were marginally significant (28°C: 2.27 ± 0.96 , 30°C: 2.50 ± 0.99 , 32°C: 2.96 ± 1.22 , $F=3.06$, $p=0.07$). The questionnaire items were scored on a 5-point Likert scale, in which 1 indicated "very satisfied" and 5 indicated "very dissatisfied"; therefore, a high score indicated low sleep satisfaction. The post hoc test showed that the participants were less satisfied with their sleep at 32°C than at 28°C ($p < 0.05$, post hoc LSD test).

When asked about sleep satisfaction at 28°C, 22 out of 26 participants were "very satisfied," "satisfied," or "neutral." For the reasons of sleep satisfaction, 9 (40.9%) selected "sleep environment (e.g., temperature, humidity, and light)," 8 (36.4%) selected "psychological tranquility," 6 (27.3%) selected "moderate activity during daytime," and 3 (13.6%) each selected "comfort of sleepwear" and "intake of foods suitable for sleep (e.g., decaffeinated coffee)." Conversely, 4 participants were "dissatisfied" or "very dissatisfied" with their sleep. For the reasons for dissatisfaction, 1 participant (25.0%) each selected "sleep environment (e.g., temperature, hu-

Table 2. Paired t-test results of subjective sleep parameters between pre- and post-nPSG

Variables	Mattress temperature	Paired differences (mean±SD)	95% CI of the difference		t	p
			Lower	Upper		
Sleep satisfaction	28°C	0.23±1.14	-0.23	0.69	1.03	0.31
	30°C	0.00±1.02	-0.41	0.41	0.00	1.00
	32°C	-0.46±1.75	-1.17	0.24	-1.35	0.19
sTST	28°C	0.58±1.21	0.09	1.06	2.44	0.02*
	30°C	0.69±1.32	0.16	1.23	2.67	0.01*
	32°C	1.04±1.43	0.46	1.62	3.71	0.001**
sSL	28°C	-0.50±1.14	-0.96	-0.04	-2.24	0.03*
	30°C	-0.42±0.90	-0.79	-0.06	-2.39	0.02*
	32°C	-0.88±0.99	-1.29	-0.48	-4.54	<0.001**
sNOA	28°C	-2.19±1.13	-2.65	-1.74	-9.87	<0.001**
	30°C	-2.19±1.33	-2.73	-1.66	-8.42	<0.001**
	32°C	-2.69±0.97	-3.08	-2.30	-14.15	<0.001**

*p<0.05; **p<0.01. nPSG, nocturnal polysomnography; SD, standard deviation; CI, confidence interval; sTST, subjective total sleep time; sSL, subjective sleep latency; sNOA, subjective number of awakenings

Table 3. Results of repeated measures ANOVA for subjective sleep parameters under the three mattress temperature conditions

Variables	28°C (A)	30°C (B)	32°C (C)	LSD	F	df	p
Sleep satisfaction	2.27±0.96	2.50±0.99	2.96±1.22	A<C	3.06	2,50	0.07†
sTST (min)	394.23±105.91	406.04±63.38	373.85±86.21		1.54	2,50	0.22
Relative sTST	3.08±0.89	3.15±0.88	3.19±0.80		0.21	2,50	0.81
sSL	2.15±1.08	2.08±0.93	2.54±0.99	B<C	3.04	1,50	0.07†
sSL (min)	29.81±30.38	34.73±39.83	39.81±32.29		1.22	2,50	0.31
Relative sSL	2.88±0.86	2.85±0.92	2.42±0.70	A>C, B>C	4.94	2,50	0.01*
sNOA	3.73±1.08	3.73±1.25	4.23±0.86		1.99	2,50	0.15
sNOA (no.)	2.96±1.34	3.37±2.28	3.85±1.82		2.27	2,50	0.11
Perception of mattress temperature	1.85±0.73	1.62±0.64	2.23±0.71	B<C	6.40	2,50	<0.01**
Feeling after waking up	3.00±0.94	2.88±0.82	2.64±0.81		1.17	2,48	0.32
Depth of sleep	4.27±1.48	3.88±1.42	3.96±1.64		0.70	2,50	0.50
Quantity of sleep	4.42±1.30	4.46±1.24	4.04±1.31		1.49	2,50	0.24
Frequency of awakenings	3.50±1.36	3.54±1.50	2.81±1.39	A>C	2.85	2,50	0.08†
Frequency of dreams	4.23±2.27	4.50±2.00	4.58±2.12		0.26	2,50	0.77
Sleep comfort	4.62±1.30	4.15±1.32	4.00±1.50		2.02	2,50	0.14

*p<0.05; **p<0.01; †p≤0.08. Data are presented as mean±standard deviation. ANOVA, analysis of variance; LSD, least significant difference; sTST, subjective total sleep time; sSL, subjective sleep latency; sNOA, subjective number of awakenings

midity, and noise), “discomfort of sleepwear,” and “not being able to sleep”; 1 participant did not respond.

At 30°C, 21 out of 26 participants were “very satisfied,” “satisfied,” or “neutral” in terms of sleep quality. For the reasons for satisfaction, 14 (66.7%) responded with “sleep environment,” 4 (19.0%) with “moderate activity during daytime,” 3 (14.3%) with “psychological tranquility,” and 1 (4.8%) each with “comfort of sleepwear” and “intake of food suitable for sleep.” Conversely, 5 participants were “dissatisfied” or “very dissatisfied” with the sleep quality. For the reasons for dissatisfaction, 2 (40.0%) responded with “sleep environment” and 1 (25.0%) each with “discomfort of sleepwear,” “inconvenience of pillows,” “inconvenience of sensors,” and “long working hours.”

At 32°C, 15 out of 26 participants were “very satisfied,” “satisfied,” or “neutral” with the sleep quality. For the reasons for satisfaction, 7 participants (46.7%) responded with “sleep environ-

ment,” 6 (40.0%) with “moderate activity during daytime,” 3 (20.0%) with “psychological tranquility,” and 1 (6.7%) each with “comfort of sleepwear” and “intake of food suitable for sleep.” Conversely, 11 participants were “dissatisfied” or “very dissatisfied” with the sleep quality. For the reasons for dissatisfaction, 10 participants (90.9%) responded with “sleep environment” and 1 (9.1%) with “discomfort of sleepwear.”

The differences among sSL was close to significance (28°C: 2.15±1.08, 30°C: 2.08±0.93, 32°C: 2.54±0.99, F=3.04, p=0.07). A higher score indicates a longer SL and participants were awarded 1–5 points if they took “<15 min,” “15–30 min,” “0.5–1 h,” “1–2 h,” and “>2 h,” respectively. The post hoc analysis showed that it took participants longer to fall asleep at 32°C than at 30°C (p<0.05, post hoc LSD test).

There were significant differences in the responses related to the comparison of SL (28°C: 2.88±0.86, 30°C: 2.85±0.92, 32°C:

Table 4. Results of repeated measures ANOVA for objective sleep parameters under the three mattress temperature conditions

	28°C (A)	30°C (B)	32°C (C)	LSD	F	df	p
TST (min)	419.53±49.86	422.61±46.45	411.78±60.39		0.41	2,50	0.67
WASO (min)	47.76±37.57	45.61±44.45	57.87±62.45		0.68	2,50	0.51
SL (min)	11.90±19.07	11.75±16.70	9.33±9.23		0.56	2,50	0.58
REML (min)	99.85±47.95	89.08±59.45	100.63±58.15		0.49	2,50	0.62
SE (%)	87.54±10.45	88.05±9.64	86.02±12.70		0.34	2,50	0.71
NOA (no.)	28.35±16.74	31.50±16.82	32.58±15.27		1.36	2,50	0.27
Stage N1 (%)	11.58±6.24	11.71±6.05	12.77±8.83		0.47	2,50	0.58
Stage N2 (%)	58.23±7.70	56.04±7.67	56.28±9.85		1.10	2,50	0.34
Stage N3 (%)	10.79±8.40	10.45±7.06	10.56±7.72		0.06	2,48	0.94
Stage REM (%)	19.40±4.13	21.81±4.87	20.40±5.86	A<B	3.34	2,50	0.04*
SAI	11.03±6.18	11.88±5.86	12.79±7.75		1.27	2,50	0.29
AHR (bpm)	61.24±13.50	64.72±6.59	61.67±12.84		0.97	2,50	0.38
HHR (bpm)	145.36±7.80	141.45±13.52	142.37±12.74		0.89	1,50	0.38
LHR (bpm)	26.88±4.06	26.42±3.00	25.95±1.80		0.84	2,50	0.44

Data are presented as mean±standard deviation. * $p<0.05$. ANOVA, analysis of variance; LSD, least significant difference; TST, total sleep time; WASO, wake after sleep onset; SL, sleep latency; REML, REM latency; SE, sleep efficiency; NOA, number of awakenings; REM, rapid eye movement; SAI, spontaneous arousal index; AHR, average heart rate; HHR, highest heart rate; LHR, lowest heart rate

2.42±0.70, $F=4.94$, $p<0.05$). In this 5-point Likert question, scores of 1 and 5 indicate that “it took a very long time to fall asleep in the experiment compared to at home (i.e., comfortable environment)” and that “it took a very short time to fall asleep in the experiment compared to at home,” respectively. The post hoc result showed that the participants felt that they needed more time to sleep at 32°C compared to at 28°C or 30°C in the experiment compared to at home (for both $p<0.05$, post hoc LSD test).

There was a significant difference in the perception of mattress temperature (28°C: 1.85±0.73, 30°C: 1.62±0.64, 32°C: 2.23±0.71, $F=6.40$, $p<0.01$), with scores of 1–3 indicating “a feeling of colder mattress temperature after sleep compared to before sleep,” “a feeling of similar mattress temperature before and after sleep,” and “a feeling of less cold mattress temperature after sleep compared to before sleep” respectively. The post hoc test showed that the participants perceived the mattress as the least cold after sleep compared to before sleep at 32°C compared to at 30°C ($p<0.01$, post hoc LSD test).

There was a marginally significant difference in the frequency of awakenings between the temperatures (28°C: 3.50±1.36, 30°C: 3.54±1.50, 32°C: 2.81±1.39, $F=2.85$, $p=0.08$). This item was scored on a 7-point Likert scale, with scores 1–7 indicating that the participants “woke up very often during sleep” to participants “did not wake up at all during sleep.” As a result of the post hoc analysis, participants perceived nighttime awakenings more commonly at 32°C than at 28°C ($p<0.01$, post hoc LSD test). The other differences among subjective sleep measurements were not significant ($p>0.05$).

Comparisons of objective sleep parameters between different mattress temperatures

A repeated measures ANOVA was performed to identify whether there was a significant difference among post-nPSG objective

parameters at each mattress temperature (Table 4). The results revealed that the difference was significant in terms of the REM sleep proportion (28°C: 19.40±4.13, 30°C: 21.81±4.87, 32°C: 20.40±5.86, $F=3.34$, $p<0.05$). The post hoc test showed a lower proportion of REM sleep at 28°C than at 30°C ($p<0.01$, LSD post hoc). The other differences among objective sleep measurements were not significant ($p>0.05$).

DISCUSSION

We explored whether T_m affects the subjective and objective sleep quality in healthy young adults. For this purpose, the sleep environment temperature was controlled at 27°C for the room and 28°C, 30°C, or 32°C for the mattress. The sleep parameters were compared during sleeping under each condition.

The self-reported questionnaires showed that participants were less satisfied with sleep at 32°C than at 28°C, and the participants perceived that it took them longer to sleep at 32°C than at 30°C. A higher proportion of participants responded that their sleep dissatisfaction was caused by the “sleep environment (e.g., temperature, humidity, and light)” at higher temperatures, with 1, 2, and 10 participants at 28°C (25.0%), 30°C (40.0%), and 32°C (90.9%). Taken together, a high mattress temperature was associated with low sleep satisfaction. Meanwhile, participants perceived that the mattress temperature was least cold at 32°C compared to at 30°C when they woke up. Compared to their usual sleep at home, participants responded that it took longer for them to fall asleep at 32°C than at 28°C or 30°C. They also had increased wakefulness at 32°C than at 28°C. In summary, we observed that participants subjectively perceived that they did not sleep well at 32°C compared to the other conditions, and suggested that the low sleep satisfaction at 32°C was mainly due to the sleep environment, including temperature.

The nPSG results showed that the proportion of REM sleep was significantly lower at 28°C than at 30°C. These findings are suggestive of a temperature-sensitive stage than non-REM sleep due to its suppressed thermoregulation and low perspiration rate [1,5,36]. However, this is not consistent with previous findings of a decreased REM proportion as the temperature increased above 28°C [6,37]. Although Tsuzuki et al. [27] revealed REM sleep changes at relatively low temperatures, they used a range of 3°C–17°C, which did not overlap with our temperature range. The proportion of REM sleep was 19.40%±4.13% at 28°C. Because the parameter was similar with the average proportion of REM sleep range of 20%–25% [38] and the subjective sleep quality was the highest at 28°C, it is difficult to confirm that the mattress temperature of 28°C disturbed the sleep. Additionally, unlike previous observations, no notable changes were found in other objective variables such as TST or non-REM sleep [37,39,40]. This might be due to the insufficient number of participants and/or because our temperature range was not wide enough to cause objective sleep differences.

Several studies have evaluated temperatures ≥32°C in their range of thermoneutral T_m [19,20,21,25]. We found no significant objective difference between at 32°C and other conditions but found relatively low subjective sleep satisfaction at 32°C, suggesting that the thermoneutral range based on objective results may contain temperatures associated with a poor subjective sleep quality. Subjective sleep indicators are useful tools for reflecting subtle but significant temperature differences that cannot be revealed with objective indicators alone. Nevertheless, few temperature studies have focused on subjective sleep quality. Subjective measurements should be used as frequently as objective ones.

There are a few limitations to this study. First, additional ambient conditions, such as humidity, were not measured. The combination of high humidity content and high T_a interferes with sleep [3,4,20]. Therefore, T_m or other ambient conditions may be manipulated to obtain accurate results. Second, the actual T_m may be lower or higher than the set mattress temperature due to several uncontrolled variables. The bed temperature was not measured in the present study, which should be measured in future studies. Finally, sleepwear was freely selected by participants and no information was available regarding the sleepwear, despite the same experimental place and beddings. Because sleepwear may affect the T_m [6], the exposed skin area and material of sleepwear should be controlled.

We investigated the effect of mattress temperatures of 28°C, 30°C, and 32°C on subjective and objective sleep measurements. Our results reveal relatively low subjective sleep quality at 32°C and a relatively low proportion of REM sleep at 28°C. Our study results are useful because we observed the differences in the thermoneutral range by focusing on T_m , which has been less commonly selected as T_a . Additionally, subjective sleep indicators were used together with objective indicators. To generalize the results, it is necessary to include more participants of various ages and carefully consider the temperature ranges. Other sleep mea-

surement tools, such as sleep diaries and actigraphy would significantly contribute to the knowledge in this field.

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Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

Availability of Data and Material

The datasets generated or analyzed during the study are available from the corresponding author on reasonable request.

Author Contributions

Conceptualization: Yu Jin Lee. Data curation: Ha Young Lee. Formal analysis: Ha Young Lee, Yu Jin Lee. Funding acquisition: Yu Jin Lee. Investigation: Min Cheol Seo, Jiyeon Shin. Methodology: Jeong Eun Jeon, Min Cheol Seo, Jiyeon Shin. Supervision: Yu Jin Lee. Writing—original draft: Ha Young Lee. Writing—review & editing: Ha Young Lee, Yu Jin Lee.

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