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*Research Article*

# Experimental Study on Sleep Quality in Naturally Ventilated Rooms under Moderate Climate Conditions

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Optimizing the thermal environment of a bedroom is desirable for good sleep. In moderate climatic conditions, natural ventilation is a viable method for enhancing the quality of sleep by improving indoor air conditions. This study examined the effects of air temperature and wind speed on sleep quality in naturally ventilated rooms with windows open and closed, during autumn. Thirteen young males in healthy conditions participated in this study. Two adjacent test rooms (for opened and closed conditions) were selected on a university campus, with standardized indoor conditions. Air temperature and wind speed were measured near the height of the participants' heads. Sleep efficiency and wake after sleep onset (WASO) were calculated using physiological wearable sensors based on heart rate and body movement. The participants completed questionnaires on thermal sensation and comfort before and after sleep. The results showed that the lowest percentage of WASO was observed when the nocturnal mean temperature was 23–24°C with a quadratic regression curve regardless of the window opening conditions. Conversely, subjective sleep satisfaction and WASO did not show any significant differences between the conditions. The results revealed no significant impact of varying thermal and airflow conditions during autumn on thermal/airflow comfort, although significant differences were observed in the thermal/airflow sensation before and after sleep. Thus, these results suggest that natural ventilation through the opening of windows might not affect thermal/airflow comfort, while a nocturnal indoor air temperature of 23–24°C is recommended for good sleep and thermal comfort, regardless of window opening conditions under moderate climate conditions.

## 1. Introduction

Sleep plays a vital role in recovering from daily fatigue and in restoring energy for bodily functions [1]. The effects of natural ventilation (NV) on good sleep have been examined [2, 3]. NV results in fresh air inside rooms [4] and physiologically affects human sleep [5–7]. Regarding the effects of indoor air quality, Strøm-Tejsen et al. conducted pilot and main field intervention experiments in Danish dormitories to investigate the effect of $CO_2$ concentration on sleep quality [5]. Experiments revealed that low $CO_2$ levels significantly improved sleep quality and next-day performance. Another intervention experiment involving 18 students found that opening windows to reduce $CO_2$ levels improved sleep efficiency and reduced wakefulness [6]. Xiong et al. conducted $CO_2$ and sleep measurements in Sydney during summer in 48 households [7]. The study found that deep sleep percentage decreased as the $CO_2$ concentration in the bedroom increased. Moreover, the study discovered that an increase of 100 ppm in the mean amount of $CO_2$ overnight caused a 4.3% decrease in sleep efficiency. Zhang et al. investigated 104 naturally ventilated bedroom environments and single-night sleep quality, in Beijing, China, where the climate is similar to that of Japan. The study found that high ventilation with low $CO_2$ concentration (mean: 672 ppm) provided significantly higher sleep efficiency compared to the low-ventilation group (mean: 2012 ppm) [8].

Temperature and airflow have been known to affect NV during sleep [9, 10]. Previous studies have already suggested proper temperature (17–28°C) for good sleep [11]. In Japan, measurements are typically conducted in actual bedrooms [12, 13]. In summer, sleep efficiency in naturally ventilated bedrooms with open windows is significantly higher than that in bedrooms with closed windows [13]. Two other field intervention experiments found poor sleep quality with windows open owing to inadequate control of noise interference in the window-open condition, which could mediate the relationship between $CO_2$ level and sleep quality [14, 15]. In Japan, during winter, with 12 young male participants, the appropriate air temperature for sleep was found to be 10°C, among the three evaluated: 3, 10, and 17°C [16]. Airflow may improve sleep patterns in high-temperature conditions [17, 18]. However, excessively high wind speeds under moderate-temperature conditions may negatively affect sleep quality.

Previous studies have investigated appropriate temperature conditions for sleep in summer and winter. The effects of open windows in summer have been studied; however, few studies have examined the exact relationship between NV and sleep quality in moderate seasons despite the frequent use of NV for indoor thermal comfort. A study on healthy elderly people showed that sleep efficiency in spring and fall differed significantly from that in summer, suggesting that each season had different effects on sleep quality [19]. Further, during moderate seasons, NV is commonly used to achieve thermal comfort in residential buildings, resulting in a wide range of indoor environmental conditions [8]. Therefore, this study selected autumn, a moderate season, and examined the effects of air temperature and wind speed under different window-opening conditions on sleep quality in 13 healthy young males. This study used two adjacent rooms (for open and closed windows) with standardized indoor conditions, on a university campus, to examine the impact of open and closed windows on sleep quality. The findings of this study can contribute to the examination of thermal/airflow sensations and comfort during sleep in moderate climate seasons with natural ventilation through window openings.

## 2. Method

*2.1. Experimental Rooms.* The experiments were conducted in two identical test rooms (3.90 m × 6.75 m × 2.59 m), which were designed to simulate a single bedroom; they were located on the fifth floor of a building in the Suzukakedai campus of Tokyo Institute of Technology (35.520386° N, 139.489116° E) (Figure 1). The two rooms were next to each other and equipped with concrete walls (without insulation), gypsum boards for the interior walls, and identical single-pane glass windows.

There were two types of window conditions: one room had a single closed window (closed), room A, while the other had its window open (opened), room B. Natural wind from the southeast blew into the room through the open window and flowed out through the louver on the lower part of the entrance door on the corridor side (Figures 1(b) and 1(c)). We set three window openings (5, 10, and 20 cm), based on outdoor weather conditions (Supplemental Figure 1). Each participant slept alone, with the windows alternately open and closed for two consecutive nights. The participants were randomly assigned to the first condition (i.e., opened or closed) to minimize the effect of the first condition on sleep. The experiment was carried out from September 22 to October 15 and was held only on sunny or cloudy days, avoiding rainy days.

*2.2. Participants.* Thirteen healthy male university students were recruited as the participants (Table 1). They had no indications of mental problems or troubles in their daily lives. They also had no sleep disorders, as confirmed during recruitment [20, 21], by the Pittsburgh Sleep Quality Index questionnaire, Japanese Version (PSQI-J). The mean PSQI-J score was 4.30 (standard deviation (SD): 1.75). An index with a score > 5 indicated a significant symptom of sleep disturbance. Therefore, the data on the sleep quality of one participant (Id = 5) were excluded from the sleep quality analysis because his PSQI-J score was 7. Consumption of caffeine, alcohol, and stimulants and intense physical activities were restricted during the experiment. All participants were paid an allowance for participating in this study at a fixed rate per night based on the regulations of the university. All protocols were approved by the University Ethics Review for Human Subject Research at the Tokyo Institute of Technology (Approval No. 2021073) and were performed according to the guidelines of the Declaration of Helsinki. The participants were informed of the purpose of the study and agreed to participate in the experiment. They had the right to quit the experiment at any time.

### *2.3. Measurement*

*2.3.1. Indoor and Outdoor Environments.* Figure 2 and Table 2 present the setting positions and specifications of the instruments, respectively. All physical measurement instruments were installed in the same manner in both rooms. The human head is the most sensitive to environmental changes [22]. Air temperature and humidity sensors (RTR-576, T&D Corporation, Matsumoto, Japan) were placed at the same height next to a pillow (height 60 cm) and attached to a tripod. The sensors were also placed outside the window with a sunlight cover. The wind direction and speed from the window were measured using a two-dimensional ultrasonic anemometer (WINDSONIC, Gill Instruments Ltd., Lymington, UK) set inside the window. A wind speed sensor (Windgraphy, KOA Corporation, Minowa, Japan) and noise meter (CENTER392, SATO-TECH, Kawasaki, Japan) were placed at the same position, next to the pillow (height 60 cm). To understand the ventilation conditions in the test rooms, the $CO_2$ concentration was measured twice using a sensor (RTR-576, T&D Corporation, Matsumoto, Japan) for each ventilation condition (closed, 20, 42.5, and 85 cm) prior to the experiment. The measurement points were set at the center of the room, at heights of 30 cm (near floor level) and 110 cm. The air change rate per hour (ACH) calculated using the $CO_2$ concentration decay technique at a 30 cm height was $1.44\,h^{-1}$ when closed and $4.49\,h^{-1}$ when fully opened. The Japan Building Standard Law of 2003 states that residential buildings require

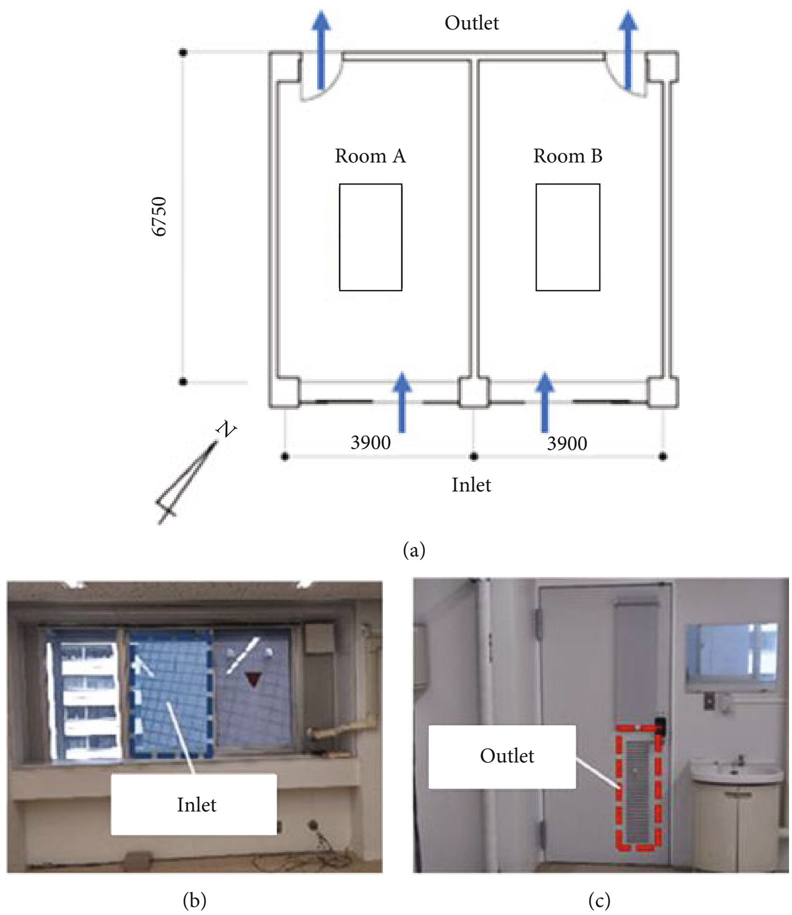


Figure 1: Experimental rooms: (a) plan of rooms A (closed) and B (opened), (b) inlet side (window), and (c) outlet side (louver).

Table 1: Demographics of participants.

| Id | Age | First condition | Dates | PSQI |
|---|---|---|---|---|
| 1 | 22 | Room A (closed) | 2021/9/22–23, 23–24 | 4 |
| 2 | 23 | Room A (closed) | 9/23–24, 24–25 | 3 |
| 3 | 22 | Room B (opened) | 9/26–27, 28–29 | 6 |
| 4 | 23 | Room A (closed) | 10/3–4 (B), 10/4–5 (A), 10/7–8 (A) | 6 |
| 5* | — | — | — | 7 |
| 6 | 22 | Room B (opened) | 9/29–30, 10/2–3 | 6 |
| 7 | 21 | Room A (closed) | 10/3–4, 10/4–5 | 5 |
| 8 | 27 | Room B (opened) | 10/5–6, 10/6–7 | 1 |
| 9 | 23 | Room A (closed) | 10/5–6, 6–7 | 3 |
| 10 | 22 | Room B (opened) | 8–9 (A), 11–12 (B), 12–13 (A) | 2 |
| 11 | 23 | Room B (opened) | 10/8–9, 11–12 | 4 |
| 12 | 23 | Room A (closed) | 10/9–10, 10–11 | 5 |
| 13 | 22 | Room A (closed) | 10/10–11, 14–15 | 4 |

*This participant was excluded from the analysis of sleep quality because his PSQI-J score was 7.

an ACH of 0.5 $h^{-1}$ with 24 h ventilation [23]. Therefore, a sufficient ventilation rate was obtained even for closed conditions.

Table 3 lists the characteristics of the bedding systems. The same bedding system with the wooden bed (0.98 m × 2 m × 0.235 m) was set in the same place in each room. The participants could select either or both futon quilts (100% polyester, *Q*) and blankets (100% acrylic, *B*) for covers based on their preferences and environmental perceptions. They were asked to bring their clothes (full-slip sleepwear S1 or half-slip sleepwear S2).

Table 4 shows bedding type and total insulation (clo) values with the covers and clothes before and after sleep.

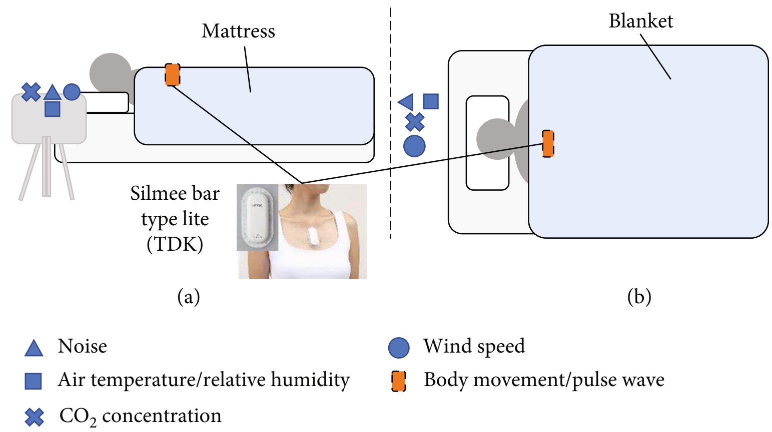


Figure 2: Setting points: (a) elevation of a bed during sleep and (b) plan for a bed during sleep.

Table 2: Specifications of the measurement instruments used in this study.

| Measured variables | Instrument model | Accuracy | Interval (min/s) |
|---|---|---|---|
| *Indoor measurement* | | | |
| Air temperature and relative humidity | RTR-576 (T&D Corporation, Japan) | ±0.3°C at 10-40°C, 2.5% RH at 15-35°C | 1 min |
| | Thermocouple type-T $\varphi$0.35 mm | ±0.1% + 0.5°C | 1 s |
| Wind speed | Windgraphy (KOA, Japan) | ±10% over 3 m/s | 100 ms, 1 s* |
| Noise level | CENTER392 (SATOTECH, Japan) | ±1.4 dB | 1 min |
| $CO_2$ concentration | RTR-576 (T&D Corporation, Japan) | ±50 ppm under 5,000 ppm | 1 min |
| *Outdoor measurement* | | | |
| Air temperature, relative humidity, and $CO_2$ concentration | RTR-576 (T&D Corporation, Japan) | ±0.3°C at 10-40°C, 2.5% RH at 15-35°C, ±50 ppm under 5,000 ppm | 1 min |
| *Physiological measurement* | | | |
| Body movement, pulse wave, and cardiac potential | Silmee Bar type Lite (TDK Corporation, Japan) | N.A. | 1 min |

*Most of the cases were measured with 100 ms, and the mean was recalculated with 1 s interval.

Table 3: Detailed measurements of bedding items.

| | Blanket (*B*) | Futon quilt (*Q*) | Mattress (*M*) | Bed |
|---|---|---|---|---|
| Size (mm) | 1400 × 2000 | 1500 × 2100 | 1200 × 2000 | 980 × 2000 |
| Thickness/height (mm) | 5 | 70 | 50 | 235 |
| Weight (kg) | 1.6 | 2.4 | — | — |
| Material | 100% acrylic | Filling: 100% feathery polyester Cover: 100% cotton | Filling: 100% rigid urethane Cover: 100% cotton | Pinewood |

Details of the bedding items and clothes were sought in the questionnaire. Bedding items in each condition were classified into three categories—(1) blanket + full-slip sleepwear ($B + S2$), (2) blanket + half-slip sleepwear ($B + S1$), and (3) futon quilt + full-slip sleepwear ($Q + S2$). A mattress was used in all cases. The clo value was calculated with the total resistance of the bedding system, including the air layer and the percentage coverage of body surface area by bedding items based on Lin and Deng [24]. There was no significant difference in the mean of clo value between closed and open conditions, regardless of the time to answer.

*2.3.2. Questionnaire before and after Sleep.* Table 5 shows the subjective sensation for the thermal and airflow environment.

Table 4: Total insulation (clo) values of each ventilation condition. The bedding type was classified into three groups based on Lin and Deng [24].

| Id | Bedding type* | Total insulation (clo) Before sleep | After sleep |
|---|---|---|---|
| *Closed window* | | | |
| 1 | 3 | 4.53 | 2.54 |
| 2 | 3 | 2.41 | 3.23 |
| 3 | 3 | 3.23 | 2.56 |
| 4 | 3, 3 | 2.54, 2.54 | 2.54, 2.54 |
| 5 | — | — | — |
| 6 | 3 | 3.23 | 4.53 |
| 7 | 1 | 1.58 | 2.16 |
| 8 | 3 | 2.54 | 2.54 |
| 9 | 1 | 1.94 | 2.53 |
| 10 | 3 | 3.23 | 4.53 |
| 11 | 3 | 2.41 | 2.54 |
| 12 | 1 | 2.16 | 2.16 |
| 13 | 3 | 3.23 | 3.55 |
| Mean in closed (SD) | | 2.77 (0.82) | 2.99 (0.87) |
| *Open window* | | | |
| 1 | 3 | 2.54 | 2.54 |
| 2 | 3 | 2.41 | 2.41 |
| 3 | 3 | 3.23 | 4.53 |
| 4 | 3 | 2.54 | 4.53 |
| 5 | 3 | 2.56 | 4.53 |
| 6 | 3 | 3.23 | 4.53 |
| 7 | 1 | 1.94 | 1.94 |
| 8 | 2 | 1.67 | 2.06 |
| 9 | 2 | 2.06 | 2.39 |
| 10 | 2, 1 | 1.94, 2.16 | 2.39, 2.53 |
| 11 | 3 | 2.41 | 3.55 |
| 12 | 3 | 3.23 | 3.23 |
| 13 | 3 | 3.23 | 3.23 |
| Mean in opened (SD) | | 2.59 (0.55) | 3.29 (1.03) |

*Bedding type. 1: blanket + full-slip sleepwear (*B* + S2). 2: blanket + half-slip sleepwear (*B* + S1). 3: futon quilt + full-slip sleepwear (*Q* + S2).

Table 5: Subjective assessment of the thermal and airflow environment.

| Options | Score |
|---|---|
| *Thermal sensation* | |
| Cold | -3 |
| Cool | -2 |
| Slightly cool | -1 |
| Neutral | 0 |
| Slightly warm | 1 |
| Warm | 2 |
| Hot | 3 |
| *Thermal comfort* | |
| Very uncomfortable | -3 |
| Uncomfortable | -2 |
| Slightly uncomfortable | -1 |
| Neutral | 0 |
| Slightly comfortable | 1 |
| Comfortable | 2 |
| Very comfortable | 3 |
| *Airflow sensation* | |
| Neither | 0 |
| Weak | 1 |
| Slightly weak | 2 |
| Slightly strong | 3 |
| Strong | 4 |
| *Airflow comfort* | |
| Uncomfortable | -2 |
| Slightly uncomfortable | -1 |
| Neutral | 0 |
| Slightly comfortable | 1 |
| Comfortable | 2 |

The thermal sensation was assessed to ascertain the thermal condition before and after sleep. We adopted the ASHRAE 7-point scale (-3: cold, -2: cool, -1: slightly cool, 0: neutral, 1: slightly warm, 2: warm, and 3: hot) for the thermal sensation, and a 7-point scale for thermal comfort, which are commonly used with seven verbal expressions [25]. Airflow sensation and comfort were assessed using 5-point scales. To calculate and estimate the clo value of the bedding system including clothes and blankets, a questionnaire sought details of the clothes, blanket types, and the percentage coverage of body surface area by bedding before and after sleep, based on the ASHRAE Standard [24, 25].

*2.3.3. Physiological Index.* Actigraphy is a cost-effective and minimally invasive alternative to polysomnography (PSG) for sleep research. PSG records electroencephalograms (EEG) for brain waves, electrooculograms (EOG) for eye movements, and electromyograms (EMG) for chin muscle tension, to classify sleep states and examine sleep processes [10, 26]. This experiment was not conducted in actual bedrooms, but in test rooms. To obtain data that minimally disturbed the sleep of participants, a vital sensor (Silmee Bar type Lite, TDK Corporation) was used for actigraphy, which was attached to the center of the chest of participants (Figure 2). In contrast to EEG, this device can more conveniently estimate sleep patterns. It measures the acceleration of the body movements of the participants and calculates their heart rate variability (HRV) from the pulse wave as well as their cardiac potential [22]. HRV was used to predict the ratio of low frequency to high frequency (LF/HF), which is used as an index of autonomic nervous system activities, and to estimate sleep stages from LF/HF. Finally, the sleep stages in the device were classified into four categories: wake, rapid eye movement (REM) sleep stage, sleep stage 1 and sleep stage 2 (Stage1+2), and sleep stage 3 and sleep stage 4 (Stage3+4). REM and non-REM (NREM) sleep stages 1 to 4 change during sleep. Sleep starts in NREM, proceeds to deeper

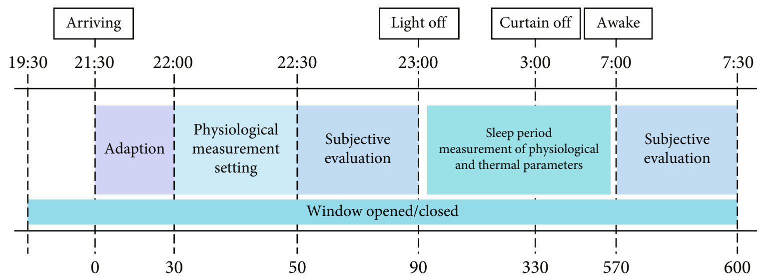


Figure 3: Experimental procedure in one night.

Table 6: Measurement results between closed and opened conditions.

| Parameters | Closed ($n = 7$) | Opened ($n = 8$) | $p$ | $t$ |
|---|---|---|---|---|
| *Thermal environment* | | | | |
| Indoor air temperature (°C) | 23.80 (0.51) | 23.10 (1.13) | ns | |
| Outdoor air temperature (°C) | 20.66 (1.81) | 20.88 (1.94) | ns | |
| Indoor relative humidity (%) | 65.58 (3.49) | 66.67 (3.18) | ns | |
| Outdoor relative humidity (%) | 82.50 (8.0) | 77.50 (3.4) | ns | |
| Indoor $CO_2$ concentration (ppm) | 586.5 (28.1) | 493.4 (24.1) | <0.001*** | 6.91 |
| Outdoor $CO_2$ concentration (ppm) | 407.6 (12.7) | 441.9 (19.1) | 0.0014** | -4.03 |
| Wind speed (m/s)[a] | 0.140 (0.01) | 0.240 (0.02) | <0.001*** | 4.15 |
| Noise level (dB) | 47.7 (0.86) | 45.25 (1.39) | 0.0014** | 4.02 |
| *Sleep quality* | | | | |
| Sleep latency (h) | 0.322 (0.20) | 0.230 (0.09) | ns | |
| Sleep efficiency (%) | 92.6 (4.90) | 89.1 (7.50) | ns | |
| Body movement frequency (%) | 0.060 (0.04) | 0.080 (0.04) | ns | |
| Awakening time (h) | 0.600 (0.40) | 0.879 (0.60) | ns | |
| Occurrence rate of WASO[b] (%) | 8.20 (5.62) | 13.0 (9.87) | ns | |
| Occurrence rate of SWS[c] (%) | 10.4 (6.90) | 12.6 (4.20) | ns | |

Mean (standard deviation (SD)). [a]Wind speed was calculated by $n$-value of 6 (closed) and 7 (opened). [b]Wake after sleep onset (WASO). [c]Slow wave sleep. $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$. ns: nonsignificant.

NREM stages (Stage3+4), and progresses through REM around 80–100 min intervals. The results of the sleep stages included wake stages, REM, Stage1+2, and Stage3+4. Stage3+4 was defined as slow wave sleep (SWS), whereas light sleep consisted of sleep Stage1+2 [27].

To account for individual differences in absolute sleep values, this study mainly used relative metrics to analyze sleep stages and quality. The sleep scoring parameters included total sleep time (TST), time in bed (TIB), sleep latency, WASO, ratio of waking state during sleep to TIB, and sleep efficiency (SE = TST/TIB × 100) [27].

*2.4. Experimental Procedures.* Figure 3 shows the schedule of the experimental procedure. In the open condition, the window was opened from 19:30 pm to 9:00 am the next morning, and in the closed condition, the window was closed for the same duration. The participants were asked to enter the assigned test room at 21:30 pm, rest for 30 min, and change their clothing to sleepwear. Beginning at 22:00 pm, the ceiling light was turned off immediately after the vital sensor was attached to the chest. The participants then went to bed and answered a subjective questionnaire via smartphones while lying down. A small light stand was installed in each test room. Before sleeping, the participants spent time with the small light on to become accustomed to the sleep environment.

The use of electronic devices was allowed from 21:30 pm to 22:00 pm, except when answering questionnaires. From 23:00 pm, all lights were turned off, and the participants slept while the automatic rolling curtain was closed on the inlet window at 3:00 am to avoid the effects of sunlight on sleep. The participants were asked to wake up at 7:00 am and report the thermal sensation of that time online in their sleeping posture. They were allowed to use an alarm to wake up on time.

*2.5. Statistical Analysis.* R (version 4.2.1) was used for the statistical analysis [28]. The normality of the measured data was assessed using the Shapiro-Wilk test, and the variance was assessed using the $f$-test. The first set of sleep data were excluded because the bedroom environment was new to the participants, meaning the participants were familiarizing

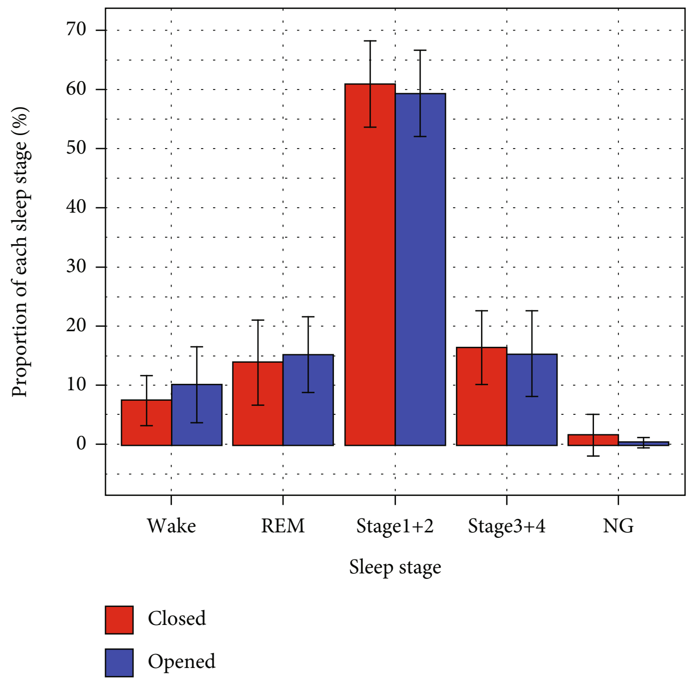


Figure 4: The proportion of each sleep stage between closed and opened.

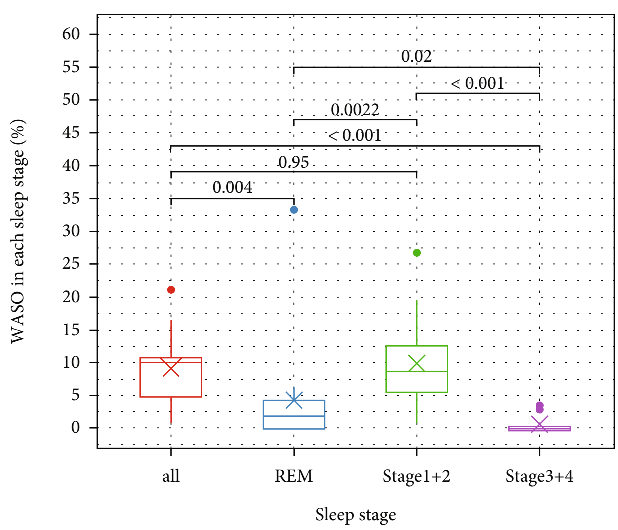


Figure 5: Proportion of WASO in each sleep stage.

themselves with using the sleep device while sleeping in the first condition. A two-tailed independent $t$-test was used for normally distributed data and the Wilcoxon rank-sum test (unpaired)/Wilcoxon signed-rank test (paired) for non-normally distributed and qualitative data. Particularly, 0.05 was adopted as significant ($p < 0.05$).

## 3. Results

*3.1. Sleep and Environmental Parameters in Closed and Opened Conditions.* The mean ± SD of sleep and environmental parameters for each window condition are listed in Table 6. These parameters were averaged between 22:00 and 7:00. The indoor/outdoor air temperature (Ta, To) and the relative humidity (RH) did not differ significantly, while the wind speed (WS) and the indoor $CO_2$ concentration were significantly different between the closed and open conditions. However, the $CO_2$ concentration did not have a relationship with the occurrence of WASO (Supplemental Figure 2). WASO (all) was defined as one accumulated wake stage throughout the night. The noise level in the closed condition was greater than that in the opened condition because of the duct noise near the room in the closed condition; however, it was low enough and did not correlate with WASO (Supplemental Figure 3).

The sleep efficiency (SE) in the open condition had a larger SD than that in the closed condition. However, there was no significant difference in the mean between the two conditions ($t(13) = 1.08$, $p = 0.299$). The occurrence of WASO did not differ significantly between the two conditions ($t(13) = -1.133$, $p = 0.277$). Other sleep parameters did not differ significantly.

*3.2. Objective Sleep Quality.* Figure 4 shows the proportion of each sleep stage in closed and open conditions. The wake stage accounted for approximately 8% of the total, with 7.37% (SD = 4.15%) for the closed condition and 10.0% (SD = 6.40%) for the open condition (both shown in mean). The respective sleep stages showed no significant differences between closed and open conditions when detailed environmental conditions were not considered.

Figure 5 shows the comparisons between the WASO occurring at each sleep stage. There were significant differences between WASO (all stages) and the ones (REM and Stage3+4), while no significant difference was observed between WASO (all stages) and one (Stage1+2). This indicates that the wake stage mostly occurred from Stage1+2.

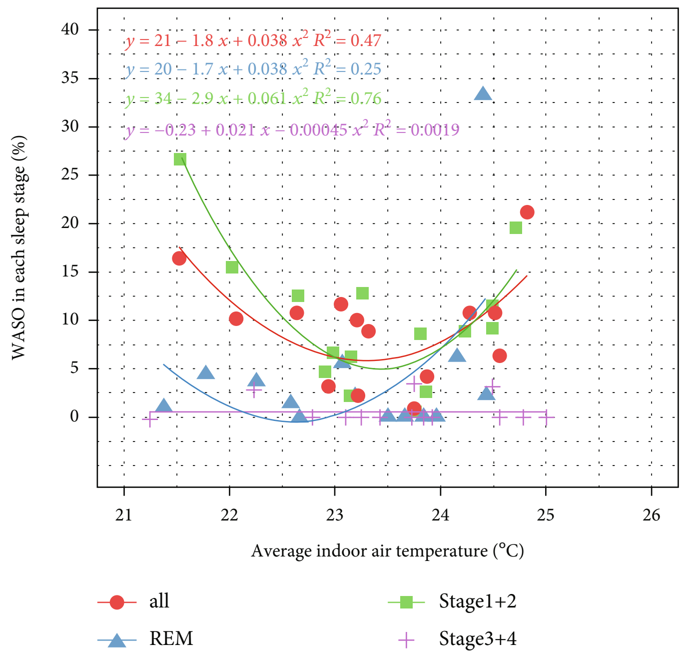


Figure 6: Proportion of WASO and air temperature in each sleep stage and regression line. Red dots and red quadratic line represent WASO for accumulating all sleep stages all night, with plots of wake stages from other sleep stages—blue (REM), green (Stage1+2), and purple (Stage3+4).

Figure 6 shows the relationship between WASO in each stage and Ta. Ta was averaged for each sleep stage. Quadratic regression was applied to the relationship between WASO and Ta. The green-dotted quadratic regression curve shows the relationship between the WASO from Stage1+2 and Ta. The red-dotted quadratic regression curve is the curve for accumulating all sleep stages. Under the temperature conditions of around 23–24°C, low WASO was recorded all night, and the regression line of Stage1+2 and Ta shows a similar tendency. However, REM and Stage3+4 were not related to Ta (REM: $R^2 = 0.25$, Stage3+4: $R^2 = 0.0019$).

To evaluate the effects of wind speed on sleep, three different temperature groups were analyzed (under 23°C, 23–24°C, and over 24°C) based on the results of Figure 6. Regardless of the temperature group, the ventilation conditions did not show significant differences in the WASO at every sleep stage.

Figure 7 shows the WASO and wind speeds for the three temperature groups divided into sleep stages. Regardless of the sleep stage, the wind speed showed different trends between the temperature groups. From the result of (a) WASO in the entire night group (all), 23–24 and over 24°C had a slope less than 1, whereas the slope under 23°C was 4. For the result of (c) WASO from Stage1+2, only the slope of 23–24°C was negative (-0.17), whereas other temperature groups were positive. Thus, these findings indicated no significant relationship between WASO and wind speed.

*3.3. Subjective Sleep Quality.* Figure 8 shows the subjective sleep satisfaction in the closed and opened groups. Sleep satisfaction was evaluated using a 7-point scale. There was no significant difference in subjective sleep satisfaction between closed and open conditions, whereas the standard deviation in opened (1.51) condition was greater than that for the closed (0.69) condition.

*3.4. Thermal Sensation and Thermal Comfort under Each Ventilation Condition.* Figure 9 shows the thermal sensation and thermal comfort in the closed and open conditions before and after sleep. Before sleep, the thermal sensation differed significantly between the ventilation conditions ($p = 0.0063$, Figure 9(a1)), whereas after sleep, the relationship did not show a significant difference ($p = 0.061$, Figure 9(a2)). The thermal comfort between ventilation conditions did not show significant differences, regardless of time (Figure 9(b1 and b2)).

Table 7 compares these sensations before and after sleep for each ventilation condition. The thermal sensation was higher before sleep than after sleep, regardless of the ventilation conditions. Thermal sensation showed a significant difference, whereas thermal comfort did not show any significant difference regardless of the ventilation conditions. At both times, the thermal sensation in the closed condition was greater than that in the open condition. Moreover, the change in the thermal sensation in the closed condition (0.73) was larger than that in the open condition (0.57). Thermal comfort increased after sleep compared to before sleep, regardless of the ventilation conditions.

*3.5. Airflow Sensation and Comfort between Closed and Opened Conditions.* Figure 10 shows the airflow sensation nd comfort between closed and open conditions before and after sleep. Before sleep, the airflow sensation was significantly different between the ventilation conditions ($p = 0.0031$, Figure 10(a1)); after sleep, the relationship also showed a significant difference ($p = 0.0081$, Figure 10(a2)). The airflow

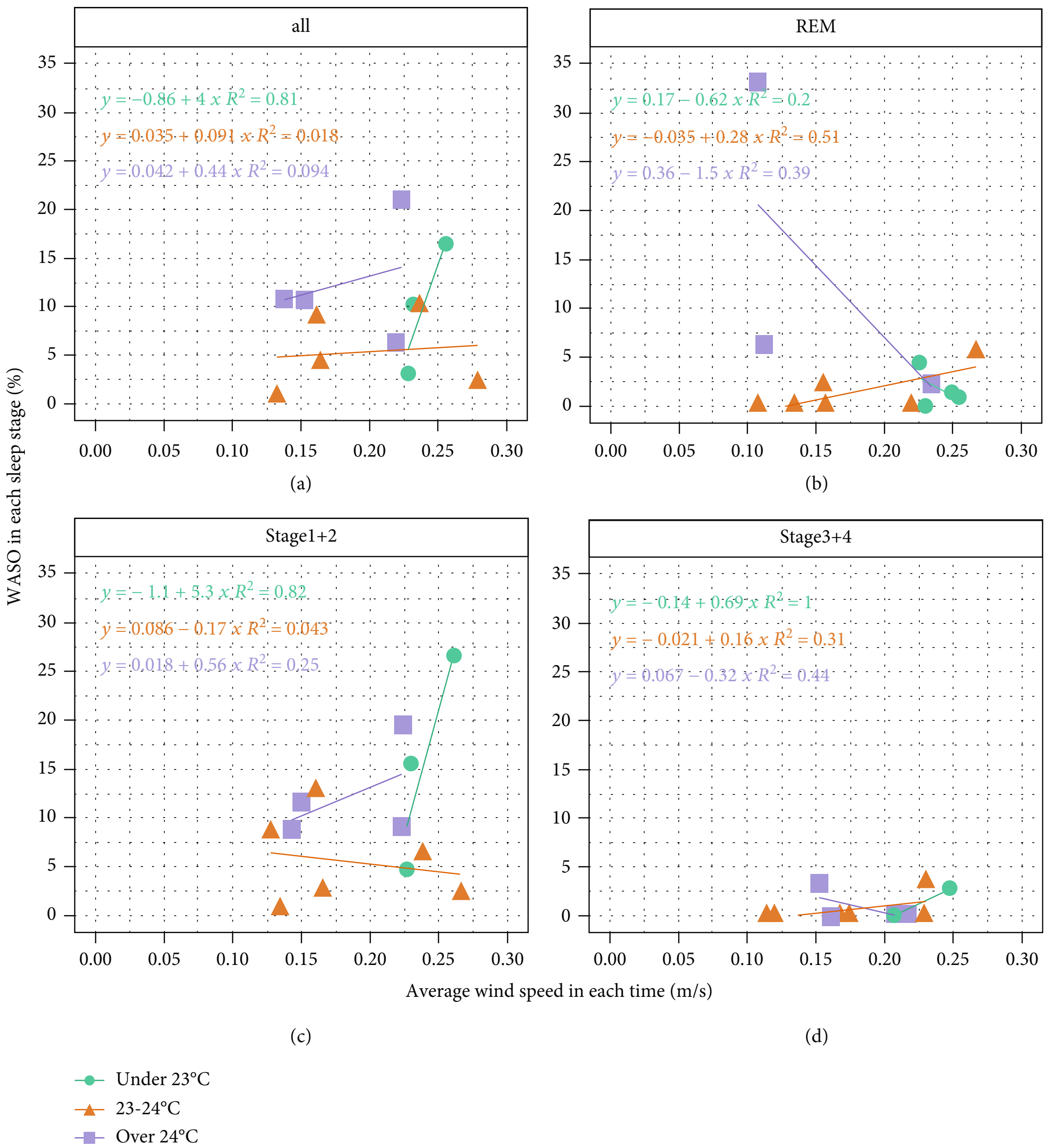


FIGURE 7: Mean wind speed and the proportion of WASO in each sleep stage with the legend of each temperature group (under 23°C, 23–24°C, and over 24°C): (a) all, (b) REM, (c) Stage1+2, and (d) Stage3+4.

comfort between ventilation conditions did not show significant differences, regardless of time (Figure 10(b1 and b2)).

Table 8 presents a comparison before and after sleep under each ventilation condition. Airflow sensation and comfort did not show any significant difference, regardless of the ventilation conditions. These findings indicate that thermal sensation was not a factor affecting thermal comfort, whereas airflow sensation was observed in the open state before and after sleep.

## 4. Discussion

This study investigated the effects of ventilation through open windows on sleep quality by conducting experiments in the same outdoor environment. Prior research on the thermal environmental and airflow effects on sleep under open-window conditions was mainly conducted in the summer. In this study, two adjacent rooms with standardized indoor conditions were used. In addition to the effects of natural ventilation that earlier studies have revealed [6, 29], this study examined the composite influences of air temperature and wind speed on sleep under natural ventilation conditions.

*4.1. Natural Ventilation and Sleep Quality.* In this experiment, the occurrence of WASO was not significantly different between the high-ventilation (opened) and low-ventilation (closed) conditions, even when the indoor $CO_2$ concentration

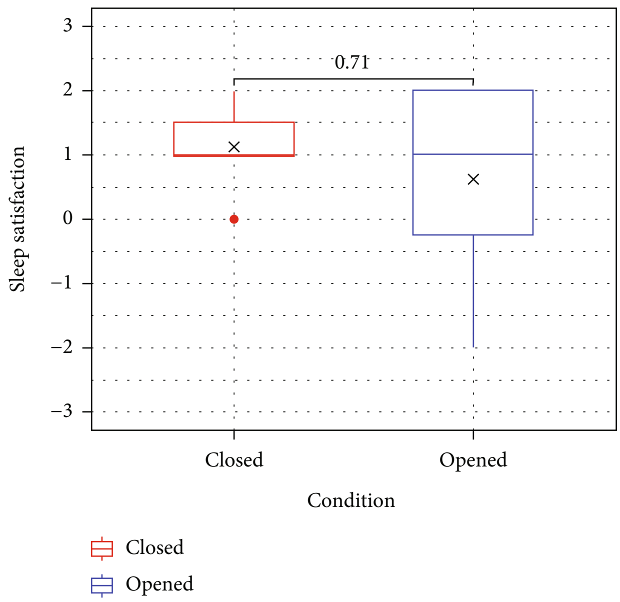


Figure 8: Sleep satisfaction between closed and opened conditions.

was different between the two conditions (Table 6 and Figure 4). However, in previous studies, window opening improved sleep quality more significantly under low $CO_2$ concentration conditions (high ventilation) than under high $CO_2$ concentration conditions (low ventilation) [5–7]. Mishra et al. measured the sleep of seventeen healthy volunteers with window/door opened and closed, showing that the lower $CO_2$ concentration caused by window openings had a lower number of awakenings, whereas the indoor air temperature with window opened was significantly lower than that with closed one (in 18–22°C conditions) [6]. Strøm-Tejsen et al. reported that sleep latency in opened condition was lower than that in the closed condition, whereas the indoor air temperature was not significantly different for male participants in a university dormitory between closed (22.6°C) and opened (22.8°C) conditions [5]. Xiong et al. conducted field measurements in the subtropical city of Sydney during summer for 48 participants under three conditions: fan, AC, and open windows or doors [7]. Although the mean air temperature was not different in the ventilation conditions around 25–26°C (fan: 26.7°C, AC: 25.3°C, and open windows and doors: 26.3°C), the bedroom $CO_2$ concentration was found to affect deep sleep (NREM) (%). Therefore, the $CO_2$ concentration may affect sleep quality under similar air temperature conditions.

Deep sleep was observed to decrease by 4.3% for every 100 ppm $CO_2$ concentration increase overnight [7]. Another previous study showed that, when the ventilation was the same between the thermoelectric air duct cooling system (TE-AD) (750 ppm) and NV (620 ppm), the sleep stage at that moment was found to easily move to other stages with a small temperature change (approximately 1.2°C) [30]. Therefore, it was suggested that air temperature during sleep had a noticeable impact on sleeping people, even under similar $CO_2$ concentration conditions.

This study showed that SE and WASO, as objective sleep quality criteria, were related to the air temperature (Figure 6), whereas $CO_2$ concentration demonstrated no significant differences in sleep quality indexes between the two ventilation conditions (Supplemental Figure 2). This might have occurred because only one participant was asleep in the test room with sufficient space during sleep, and the ACH was more than 1 even when the window was closed. WASO was not significantly different between closed and open ventilation (Table 6), whereas a previous study showed that natural ventilation through window opening affected objective sleep quality with significant differences between window opening and closing [6]. The air temperature range in this study (around 21°C to 25°C) was different from that of the previous study (18°C–22°C) [6]. Therefore, under moderate climatic conditions, window opening may not disturb sleep quality.

*4.2. Indoor Air Temperature and WASO with Natural Ventilation.* Haskell et al. showed that WASO became lower with the increase in air temperature (from 21°C to 29°C) for naked participants [31]. The highest WASO was recorded at 21°C, whereas the lowest WASO was 29°C under 21°C to 29°C. In this experiment, the relationship between indoor air temperature and WASO was shown as a quadratic function in the range from 21°C to 25°C, and the lowest WASO was shown under around 23°C to 24°C (Figure 6). Haskell et al. conducted a study on naked participants; however, in the present study, the participants brought their own clothes and selected bedding items. Therefore, the relationship between WASO and air temperature differed from that in the previous study because of the clothes worn during sleep.

Previous studies examined the most appropriate temperature for sleeping in Japanese winter, with the three thermal conditions: 17, 20, and 23°C [32]. The study showed that 20°C was thermally most comfortable in the wake stage, whereas 23°C provided the shortest sleep latency among the three conditions. In summer, sleep measurement was conducted under three thermal conditions (23, 26, and 30°C) [33]. Under the condition of 26°C, the occurrence of SWS was significantly the largest, and sleep latency was significantly the shortest. Therefore, the appropriate temperature for sleep might differ according to Japanese seasons, and the range of the appropriate temperature might be from 20°C in winter to 26°C in summer. In this study, the air temperature that showed good sleep quality was 23°C to 24°C. Thus, this result was consistent with previous studies considering seasonal appropriate air temperatures.

The previous study that conducted measurements for Japanese summer showed that the lowest WASO was around 25°C in the temperature range from 19°C to 34°C [34]. The present study also showed a similar relationship between WASO and air temperature (Figure 6). Therefore, the appropriate temperature of 23–24°C in this study was consistent with that in the previous study of the field measurement, whereas the air temperature in the present study was lower than that in the previous study. This may be because the present study was conducted under moderate climatic conditions.

In this study, wind speed did not impact WASO from 0.12 m/s to 0.27 m/s (Figure 7). Moreover, WASO did not show any significant difference between the closed and

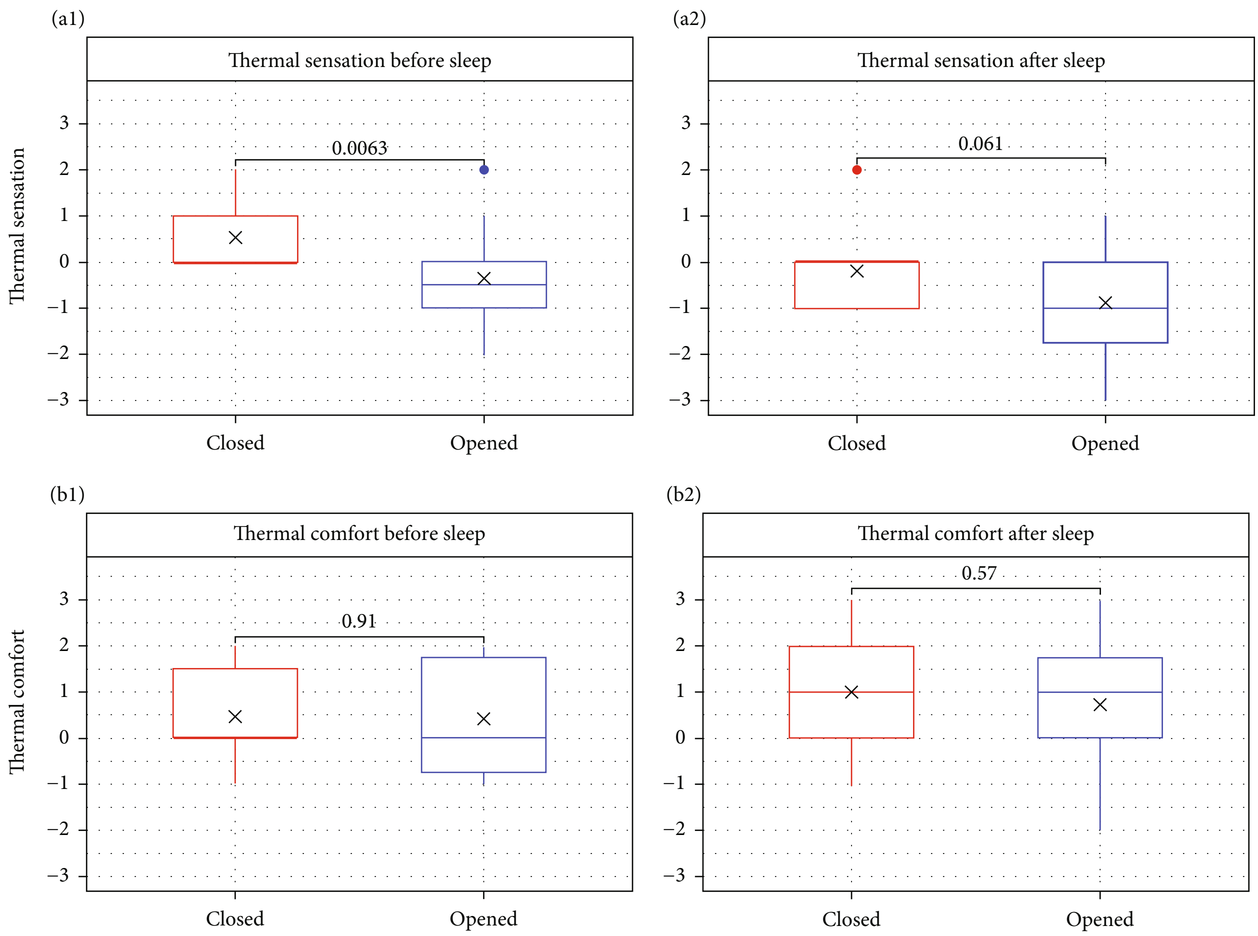


Figure 9: Thermal sensation and comfort before and after sleep between closed and opened conditions. (a1, a2) Boxplots of thermal sensation before and after sleep in closed and open conditions. (b1, b2) Boxplots of thermal comfort before and after sleep in the closed and open conditions. The closed condition is represented in red, and the open condition is represented in blue. The *p* values are shown for both ventilation conditions. The scales for thermal sensation and comfort are listed in Table 5.

Table 7: Thermal sensation and thermal comfort before and after sleep.

| | | Before sleep | After sleep | *p* |
|---|---|---|---|---|
| Thermal sensation | All ($n = 29$) | 0.10 (0.94) | −0.55 (0.99) | 0.012* |
| | Closed ($n = 15$) | 0.53 (0.64) | −0.20 (0.78) | ns |
| | Opened ($n = 14$) | −0.36 (1.01) | −0.93 (1.07) | ns |
| Thermal comfort | All ($n = 29$) | 0.45 (1.15) | 0.86 (1.25) | ns |
| | Closed ($n = 15$) | 0.47 (1.13) | 1.00 (1.20) | ns |
| | Opened ($n = 14$) | 0.43 (1.22) | 0.71 (1.33) | ns |

Mean (standard deviation (SD)). *$p < 0.05$.

opened groups (Table 6). Previous studies reported high WASO at high-temperature conditions [35] and that wind speed positively affected sleep quality under high-temperature conditions [11]. Further, airflow significantly impacted WASO in high-temperature conditions (32°C vs. 32°C with fan [17]). Previous studies have demonstrated that natural ventilation via window opening can have a positive impact on sleep quality under conditions of high $CO_2$ concentrations (mean in open: 700 ppm, mean in closed: 1150 ppm) [6]. Therefore, at high $CO_2$ concentrations, opening windows for natural ventilation under moderate climate conditions may improve sleep quality in conjunction with temperature. In this study, there was a significant difference in $CO_2$ concentration between the closed and opened conditions (Table 6). However, the concentration ranged between 460 and 600 ppm. In terms of indoor air quality, $CO_2$ concentration under 750 ppm during sleep was concluded as not disturbing the sleep quality range [3]. Therefore, $CO_2$ concentration in this experiment was not considered high enough to disturb sleep. Further research is required to clarify the effect of window openings on sleep

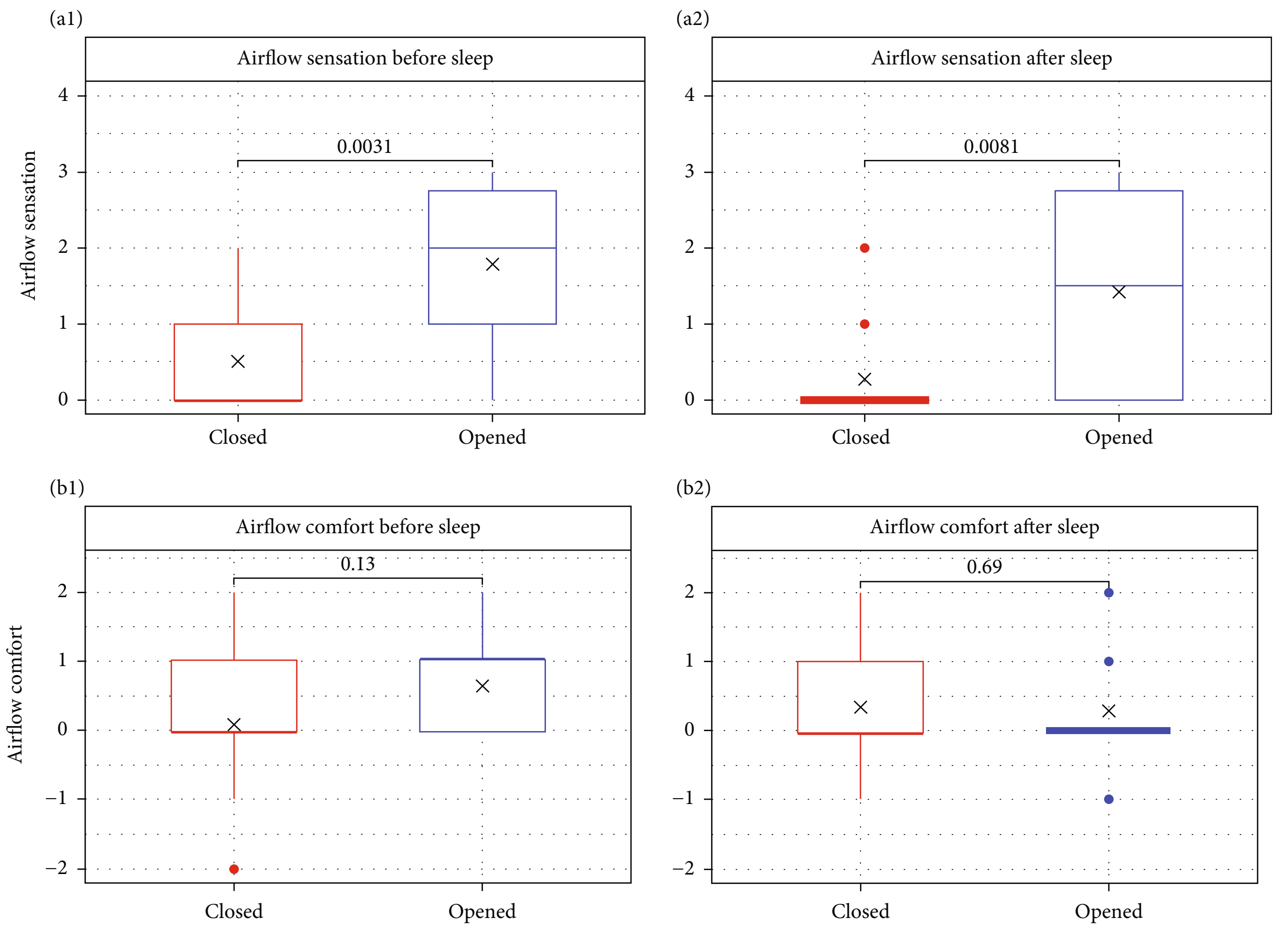


Figure 10: Airflow sensation and comfort before and after sleep between closed and opened conditions. (a1, a2) Boxplots of airflow sensation before and after sleep in closed and open conditions. (b1, b2) Boxplots of airflow comfort before and after sleep in the closed and open conditions. The closed condition is represented in red, and the open condition is represented in blue. The $p$ values are shown for both ventilation conditions. The scales for the airflow sensation and comfort are listed in Table 5.

Table 8: Airflow sensation and airflow comfort before and after sleep.

| | | Before sleep | After sleep | $p$ |
|---|---|---|---|---|
| Airflow sensation | All ($n = 29$) | 1.14 (1.16) | 0.83 (1.13) | ns |
| | Closed ($n = 15$) | 0.53 (0.92) | 0.27 (0.59) | ns |
| | Opened ($n = 14$) | 1.79 (1.05) | 1.43 (1.28) | ns |
| Airflow comfort | All ($n = 29$) | 0.37 (0.86) | 0.31 (0.81) | ns |
| | Closed ($n = 15$) | 0.13 (0.99) | 0.33 (0.82) | ns |
| | Opened ($n = 14$) | 0.64 (0.63) | 0.29 (0.83) | ns |

Mean (standard deviation (SD)).

quality under high indoor $CO_2$ concentrations and moderate climatic conditions.

WASO did not show any relationship with wind speed under natural ventilation conditions (Figure 7). Airflow induction should not be considered in moderate climates and low $CO_2$ concentration conditions of less than 600 ppm. A previous study showed that wind speed in bedrooms was $0.04 \pm 0.01$ m/s under the window opening condition [13], whereas wind speed under the opened condition in this experiment was 0.24 m/s. This suggests that the wind speed in this study was higher than that in actual bedroom conditions. However, no effects of wind speed on sleep quality were observed in this study.

Thus, WASO was lower under 23–24°C than under other nocturnal indoor air temperatures, regardless of ventilation conditions, whereas wind speed did not show any relationship with WASO. The recommended temperature in this study (23–24°C) under moderate climate conditions was within the range of that of the previous studies (i.e., winter and summer).

*4.3. Thermal and Airflow Sensation and Natural Ventilation during Sleep.* In this experiment, thermal comfort did not show any significant differences between the closed and opened conditions both before and after sleep, whereas thermal sensation was significantly different before sleep between the closed and opened conditions (Figure 9). A previous study examined sleep quality and thermal sensation and comfort among three thermal conditions (23, 26, and 30°C) [33]. The result showed that, under the 23°C condition, thermal comfort was significantly different between before and after sleep. This study did not observe any significant differences in thermal comfort before and after sleep (Table 7). In addition to thermal sensation and comfort, the airflow comfort did not show any significant differences between the closed and opened conditions, whereas the airflow sensation was significantly different before and after sleep. These results suggest that thermal and airflow comfort were not affected by window opening, whereas thermal and airflow sensations were significantly different between closed and opened windows with low wind speeds under moderate climate conditions.

In this experiment, neither ventilation condition showed any significant differences in the thermal sensation and comfort before and after sleep. In a previous study, thermal comfort was significantly lower before sleep than after sleep under the 23°C condition [33]. Therefore, the results indicate that thermal comfort was required differently between the waking and sleeping states, whereas there were no thermal comfort standards in sleeping compared to the current standard (EN 15251, ASHRAE 55-2010) [25, 36]. This experiment showed that thermal comfort, airflow sensation, and airflow comfort were not significantly different before and after sleep (Tables 7 and 8); however, thermal sensation was significantly different (Tables 7 and 8). In this experiment, the temperature range was from 21°C to 25°C. Thermal and airflow comforts did not change significantly under the thermal conditions. The automatic curtain prevented wind induction at 3:00 h. However, airflow sensation was significantly different after sleep between closed and opened conditions, in addition to before sleep. Therefore, physiological adaptation may differ before and after sleep, even when wind induction is prevented by an automatic curtain.

## 5. Limitations and Future Works

A previous study examined bedding microclimate temperature during sleep under high-temperature conditions [35] to determine environmental stability. In the present study, bedding microclimate temperatures were not recorded. However, the clo value after sleep was larger than that before sleep (Table 4), regardless of the ventilation conditions. This suggests that the bedding microclimate temperature should be stable with the behavioral adjustment of the participants. Further studies are required to measure the bedding microclimate temperature with natural ventilation through a window opening to identify the stability of the bedding system when examining the effects of window opening.

Previous studies have reported that $CO_2$ concentration in bedrooms differs significantly between closed and open bedrooms [5–7, 15, 29]. This study also showed the difference in the indoor $CO_2$ concentration and wind speed between closed and opened conditions (Table 6), while ACH in closed conditions was more than 1 $h^{-1}$, which satisfied the minimum value of 0.7 $h^{-1}$ in the bedroom by EN 16798-1:2019 [37]. This means that the fresh-air induction in this study might be more than that in actual bedrooms under general conditions. Moreover, several previous studies have measured multiple people in a single room, such as a student dormitory [5, 15]. The effects of high $CO_2$ concentrations under multiple people conditions might be larger in comparison with those of the present study, which had one participant sleeping in the room during the experiment. Therefore, it is necessary to consider the number of people in a room when comparing the effects of $CO_2$ concentration.

## 6. Conclusion

This study analyzed the relationships among indoor air temperature, wind speed, and sleep quality in naturally ventilated rooms under moderate climatic conditions. The following conclusions were drawn:

(1) Wind speed was significantly different between closed (0.14 m/s) and open (0.24 m/s) conditions, while the relative indoor/outdoor air temperatures and the relative humidity did not differ significantly

(2) WASO was estimated as the lowest from the quadratic regression curve at 23–24°C, regardless of the windows being open or shut, and the effects of wind speed on sleep were limited under low wind speed conditions. The temperatures obtained were in the same range as those measured during winter and summer (i.e., 20–26°C) in prior studies. In this temperature range, opening windows does not disturb sleep even if the windows are opened during sleep to maintain good indoor air quality

(3) While $CO_2$ concentration was significantly different between the closed and open window states, subjective sleep satisfaction and objective sleep quality were not significantly different in both states

(4) Thermal and airflow sensations were significantly different when windows were closed and opened, while thermal and airflow comforts were not significantly different before (22:30–23:00) and after sleep (7:00–7:30)

Therefore, this study suggests the recommended temperature range for good sleep as 23–24°C and that natural ventilation through opened windows may have no effect on participative or objective sleep quality under moderate climate conditions. Moreover, thermal/airflow *comfort* may not be affected by window opening during sleep, even if the thermal/airflow *sensation* was found to be different between window-closed and window-open conditions. This implies that window-open conditions can be selected when the indoor $CO_2$ concentration increases (e.g., due to multiple occupants, small rooms, and low air change rate) without affecting sleep quality by temperature change and airflow during sleep.

## Data Availability

Data sharing is not available for this article, as no datasets were generated or analyzed during this study. When applying to University Ethics Review for Human Subject Research at the Tokyo Institute of Technology, we declared not to disclose the data to others.

## Conflicts of Interest

None of the authors have any conflict of interest.

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## Supplementary Materials

Supplemental Figure 1: width of the window opening and outdoor air temperature. Supplemental Figure 2: indoor $CO_2$ concentration and WASO (%). Supplemental Figure 3: sound level and WASO (%). *(Supplementary Materials)*

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