Effects of Bedroom Environment on Average Heart Rate During Sleep in Temperate Regions: Winter Conditions in Healthy Males in Their Twenties with Average BMI

Abstract: The nocturnal average heart rate was found to correlate more strongly with mortality rates than the resting heart rate or 24-hour average heart rate. This study aimed to identify the environmental factors that most significantly affect the day-to-day variability of average heart rate during sleep (SHR[1]) during winter. Measurements were conducted in the participants' usual bedrooms of nine healthy male participants in their twenties with an average BMI, living in a temperate region. The measurement periods were from December 1, 2022, to March 8, 2023, and from December 1, 2023, to February 6, 2024. In addition to the heart rate, body movement, room, radiant, and bed microclimate temperatures, carbon dioxide concentration, relative humidity, and illuminance were measured. The results demonstrated that the average room and radiant temperatures during the measurement period had a significant negative correlation with the average SHR during the measurement period, with correlation coefficients of -0.83 and -0.91, respectively. Using a multilevel structural equation model, the most explanatory factors for SHR were found to be body movement, operative temperature, bed microclimate temperature, carbon dioxide concentration, and the interaction term between the bed microclimate temperature and carbon dioxide concentration. Overall, a deeper understanding of the impact of environmental conditions in winter on sleep heart rate could facilitate the design of environments that stabilize SHR.

Keywords: Operative temperature, Average heart rate during sleep, Winter, Field survey, Thermal environment.

1. Introduction

The nocturnal average heart rate is a biomarker associated with mortality and other health outcomes more than RHR, which is the number of heartbeats per minute when a person is at rest [1–3]. These studies were conducted on large populations and did not statistically consider factors such as the indoor environment during the investigation. However, few studies have focused on the relationship between the nocturnal average heart rate and the bedroom environment. Identifying the environmental factors that affect the nocturnal average heart rate is necessary to utilize it as an individual-level biomarker, and can be effective in designing and planning bedroom environments to maintain lower heart rates.

The relationships between SHR are demonstrated in the first part of this series [4] (Note 1), along with the participants' usual bedroom environment in healthy males in their twenties with an average BMI living in Japan during the summer. The operative temperature showed the highest significant correlation with SHR among the bedroom environmental factors. No significant correlations were observed with the relative humidity, carbon dioxide concentration, or illuminance. The SHR was significantly correlated with the BM, including turning over during sleep, in addition to the bedroom environment.

Abbreviations

RHR: Resting heart rate
SHR: Average heart rate during sleep [beats/min]
BM: Body movement rate during sleep [times/min]
DIC: Deviance Information Criterion
MCMC: Markov Chain Monte Carlo

According to Madaniyazi et al. [5], a study on the average heart rate with respect to outdoor temperature in Chinese individuals showed that the RHR fluctuated by approximately 2 [beats/min] depending on the variation in outdoor temperature, with the lowest value around 22 [°C] and the highest around 0 [°C], following a cubic polynomial trend. Quer et al. [6] conducted a 2-year cohort study in the United States and found that RHR, calculated using Fitbit's proprietary formula, varied seasonally, showing the highest value in January and the lowest in July, with a difference of approximately 2 [beats/min] for both men and women. These findings suggest that the effect of the thermal environment on heart rate during sleep may differ between summer and winter.

In this study, we focused on SHR in winter and aimed to clarify whether the environmental factors influencing its day-to-day variability are similar to those in summer, or if different factors contribute. The factors considered were: room, radiant, bed microclimate, and daytime outdoor temperatures, carbon dioxide concentration, relative humidity, and illuminance. The experiment was conducted in the participants' home bedrooms, similar to an earlier study [4]. The heart rate was measured using a mat-type sensor capable of non-contact/non-restrictive measurements. To reduce the burden on the participants and maintain normal sleep conditions, no specific external factors were imposed, making this an observational study.

2. Methods

2.1 Experimental Method and Measurement Factors

Although the experimental methods were the same as those described in the first part of this series [4], differences existed in the number of participants and the measurement period. The experiment involved nine healthy male participants (A1–A9) with no sleep disorders, residing in Osaka, Hyogo, and Yamagata prefectures. The study was conducted in each participant's bedroom (Note 2). The measurement periods were from December 1, 2022, to March 8, 2023, and from December 1, 2023, to February 6, 2024. Table 1 shows the sex, age, bedroom location, primary daytime location, measurement period, and number of continuous overnight heart rate data points from bedtime to waking. Data from days when the participants consumed alcohol, took medication, had <5 h of sleep, or had >10 min of missing heart rate measurements during the night were excluded from the data count. Table 2 lists the measurement parameters. Figure 1 illustrates the measurement setup in the bedroom of participant A2.

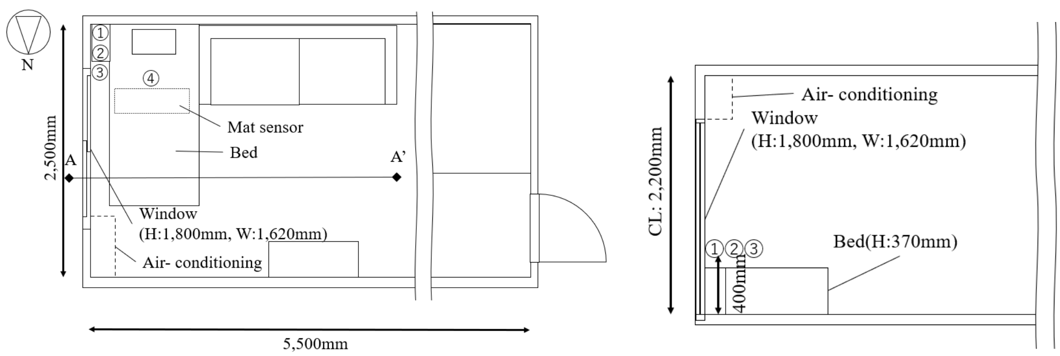


Figure 1: Example of Measurements in the Participant's Bedroom

Locations ① to ④ in the figure correspond to the positions of measurement devices for the parameters listed in Table 2.The upper figure (a) shows the Floor Plan of Participant A2's Room.The lower figure (b) shows the cross-sectional view of the A-A' cut section in the plan view.

For physiological measurements, a pressure-based mat sensor (aams, Biosilver Co.), which was validated for heart rate measurement accuracy in an earlier study [7, 8], was used. The sensor was placed under the mattress of the participant's bed, positioned between the participant's shoulder blades and waist, to continuously and non-intrusively measure body movement and heart rate. The environmental factors listed in Table 2 were measured as follows: ① Carbon dioxide concentration near the head using TR-76Ui (T&D Corporation), ② illuminance and temperature/relative humidity near the head using TR-74Ui (T&D Corporation), ③ indoor radiant temperature near the head using a thermocouple inserted into a globe connected to a UX120-014M data logger (ONSET Corporation), and ④ bed microclimate temperature using a temperature sensor coated with TPE resin placed within the bed sheets, measured with a TR-73U data logger (T&D Corporation). Preliminary surveys confirmed that none of the participants used fans during sleep and that air conditioning with direct airflow was not used. Another preliminary measurement revealed that the wind speed did not exceed 0.2 [m/s] (Note 3). Therefore, wind speed measurements were not conducted.

The participants were asked to complete questionnaires about their daily activities before bedtime and self-reporting their bedtime and wake-up time after waking up immediately (Note 4). The study was observational, and no specific conditions were imposed on the participants during sleep to minimize interference with their normal sleep patterns.

2.2 Methods for Analyzing Measurement Factors

The sleep onset time was defined as the time when body movement ceased for 5 min following the self-reported bedtime from the wake-up questionnaire. The wake-up time was based on self-reported wake-up time from the same questionnaire. The sleep duration was calculated from these values. The average values and standard deviations of the physiological metrics and environmental factors during sleep were used in the analysis. SHR [beats/min] was defined as the average heart rate during sleep. For environmental factors, the average and standard deviation during sleep were calculated for Ta [°C], Hc [%], Tr [°C], Tb [°C], CO_2 [ppm], and Lx [lx] (see Glossary), with "$_{Ave}$" and "$_{SD}$" appended to the symbols, respectively.

Typically, physiological metrics during sleep are influenced by posture, bedding, and clothing. However, this study focused on day-to-day comparisons based on night averages and standard deviations. Changes in sleep posture were assumed to be reflected in body movements, which were evaluated for their impact on SHR. As shown in Table 3, the clothing differences between days were negligible; thus, clothing variability was considered nonexistent. Bedding variations, particularly the use of duvets, were assumed to affect the bed microclimate temperature.

The operative temperature OT_{Ave} [°C] was calculated using Ta_{Ave} and Tr_{Ave} (see Glossary). The daytime outdoor temperature To [°C] (see Glossary) was obtained from the Japan Meteorological Agency data [9], representing the average temperature from 8 AM to 5 PM at the participants' daytime locations or the nearest locations listed in Table 1.

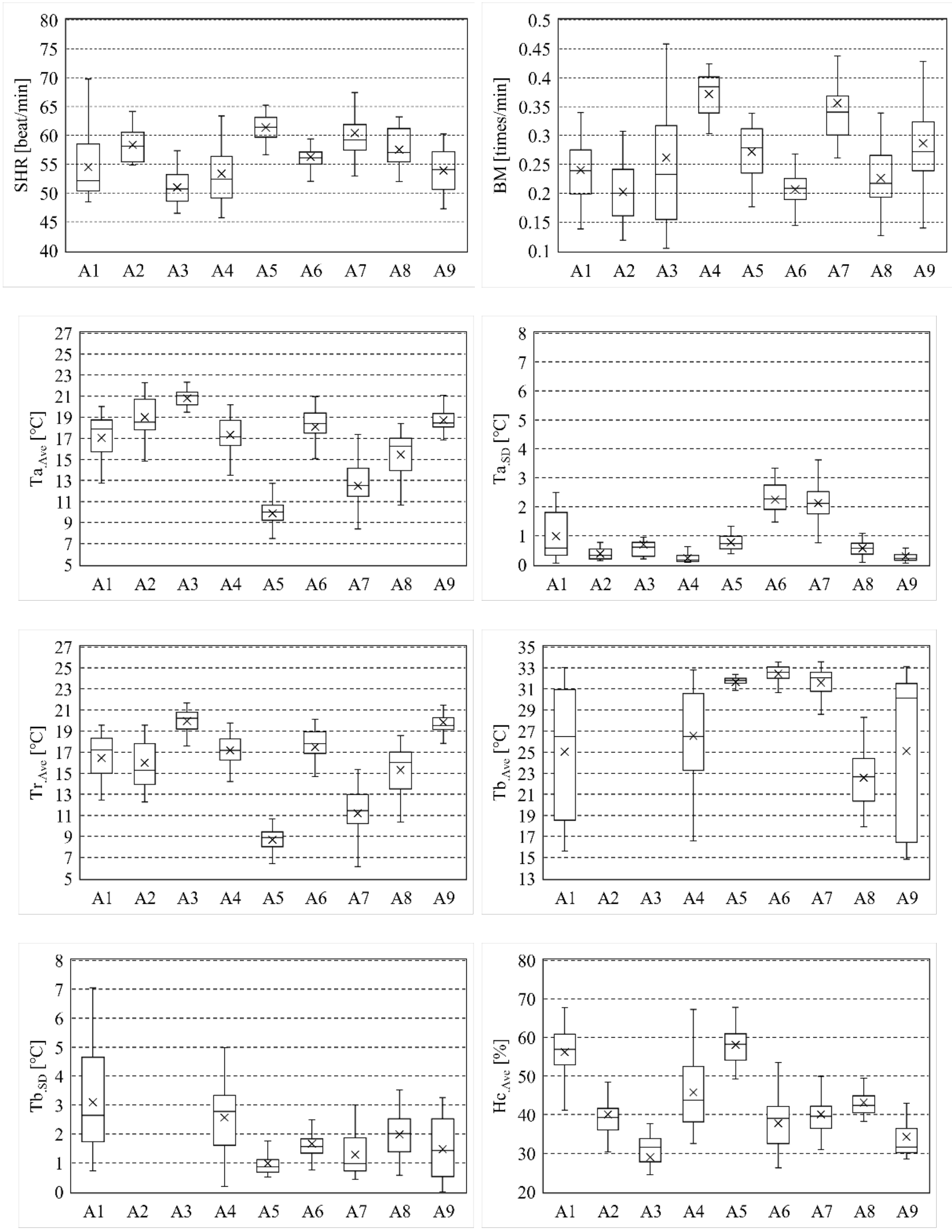
Body movement was detected every 0.5 s; if detected, it was marked as 1, otherwise 0, and the total for 1 min was summed to 120 counts (CL_{1min}), with CL_{1min} greater than 1 indicating that minute's body movement (B_{1min}) was 1 [time/min]. The total body movements during sleep (B_{total} [times]) were divided by the sleep duration [min] to calculate the BM [times/min].

3. Results and Discussion

3.1 Range of Measurements for Each Participant

Table 4 presents the average and standard deviation of each participant's bedtime and sleep duration. Some variability in bedtime was observed, with participants A4 and A9 often going to bed near dawn; however, there was no apparent reversal of day and night sleep patterns or any evidence of significantly suggestive sleep disorders.

Figure 2 shows the distributions of the SHR, BM, Ta_{Ave}, Ta_{SD}, Tr_{Ave}, Tb_{Ave}, Tb_{SD}, Hc_{Ave}, $CO_{2\,Ave}$, $CO_{2\,SD}$, Lx_{Ave}, and OT_{Ave} for each participant. The SHR tended to be lower in participants A1, A3, and A4, who lived in the Kinki region (Osaka City and Toyooka City), than in participants A5 to A8, who lived in Yonezawa City. The BM was relatively high for participants A4 and A7, with A3 showing marked day-to-day variation. The mean value of BM for all participants except A4 and A7 was within the range of 0.2–0.3 [times/min].



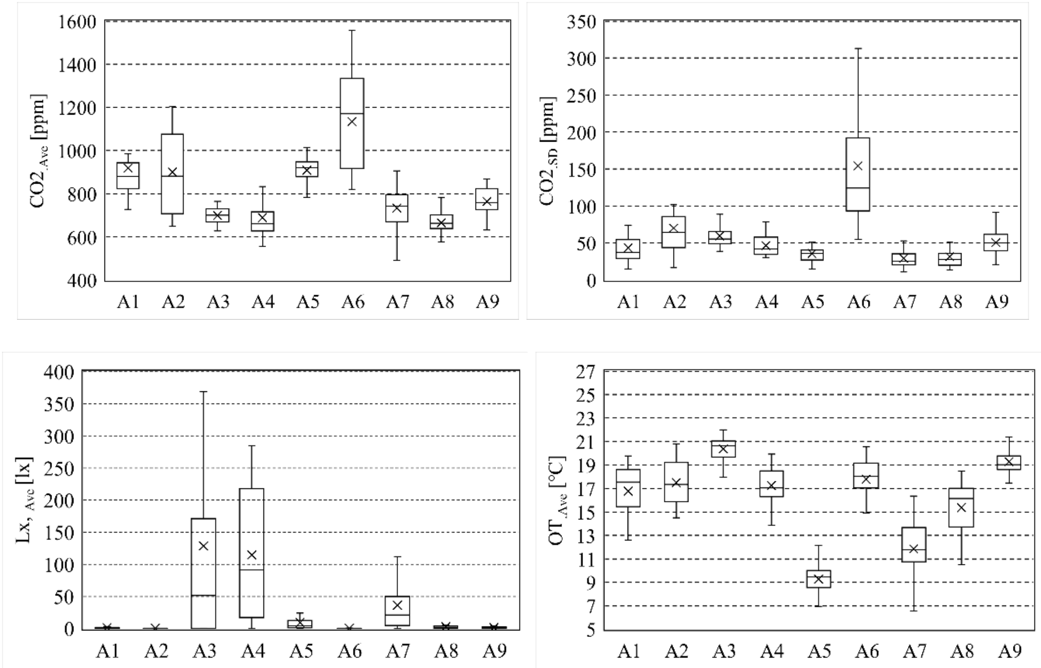


Figure 2: Measurement Results in the Participants' Bedrooms

The box plot shows the distribution of the data for each participant. The box represents the interquartile range from the first quartile to the third quartile, with the line inside the box indicating the median. The whiskers extend to the minimum and maximum values. The × symbol represents the mean. (a) SHR, (b) BM, (c) Ta,Ave, (d) Ta,SD, (e)Tr,Ave, (f) Tb,Ave, (g) Tb,SD, (h)Hc,Ave, (i) CO2,Ave, (j) CO2,SD, (k) Lx,Ave, (l) OT,Ave

Regarding room temperature Ta_{Ave} and radiant temperature Tr_{Ave}, participants A1–A4 from the Kinki region had relatively higher temperatures than participants A5–A8 from Yonezawa City. However, A6 had temperatures similar to those of the Kinki region group, whereas A9 had higher temperatures. Table 5 shows the number of days each participant used air conditioning for heating during the night. According to the questionnaire, no heating devices other than air conditioners were used. Participants A1, A2, A3, A6, and A9 used air conditioning frequently, with A2, A3, and A9 using it every night. Participants A4, A5, A7, and A8 did not use any heating devices. This likely explains the high room temperatures observed at sites A6 and A9, despite being in the relatively cold region of Yonezawa City.

For Ta_{SD}, participants A2, A3, and A9, who frequently used air conditioning, showed a range within 1 [°C], whereas A1 and A6 exhibited relatively larger nightly fluctuations. This could be due to the intermittent operation of heating, such as with the timer settings. Participants A4, A5, A7, and A8, who rarely used heating, showed differences in the range of values, which were likely influenced by the insulation performance and ventilation conditions of the rooms.

Regarding the bed microclimate temperature Tb_{Ave}, participants A1, A4, A8, and A9 experienced nights when the temperature dropped to near room temperature and nights when it was high, likely owing to body heat. This variation is similar to earlier findings [10] and can be attributed to the displacement of the duvets or the relative position of the sensor and the participant's body. Although participant A5 did not use heating, the bed microclimate temperature was higher than the room temperature, indicating the effect of body heat. As shown in Table 6, participant A5 used an electric blanket; however, the temperature was similar to that of participants A6 and A7, who did not use an electric blanket. For participants A5–A7, the mean and variance of Tb_{SD} were similar to or smaller than those of Ta_{SD}, suggesting that sleep posture was constant. Furthermore, from Table 6, it is evident that little day-to-day variation in duvet was observed for participants A5–A7. In day-to-day comparisons with the same bedding and constant sleep posture, the average bed microclimate temperature was affected by the average room temperature, and the day-to-day variation in the bed microclimate temperature was smaller than that at room temperature. This trend is similar to earlier findings [10]. Due to measurement issues, data for participants A2 and A3 are not displayed.

The relative humidity Hc_{Ave} was notably low for participant A3, whereas participants A1 and A5 exhibited relatively high humidity levels. Carbon dioxide concentration $CO_{2\ Ave}$ exceeded 1000 [ppm] on some days for participants A2, A5, and A6, with A6 exceeding 1400 [ppm] on certain days, and the $CO_{2\ SD}$ values were also high. This indicated that ventilation was ineffective on some nights for participant A6.

The illuminance, Lx_{Ave} was relatively high for participants A3 and A4. Participant A3's bedroom had windows on both sides, and both A3 and A4 reported later waking times (Table 3), suggesting the effect of sunlight through the windows.

For OT_{Ave}, compared with Ta_{Ave}, the temperatures were lower for participants A2, A3, A5, and A6. This suggests the influence of Tr_{Ave} being lower, which is due to the lower outdoor air temperature.

3.2 Relationship Between Regional Temperature Differences and SHR

Figure 3 shows the regional differences in daytime outdoor temperatures during the measurement period. According to Table 1, some participants spent their daytime in Higashi-Osaka City. However, because no meteorological data were available for Higashi-Osaka City, data from Osaka City, the nearest location with a similar elevation (within 5 [m]), were used. One-way ANOVA confirmed significant differences among the three regions ($P<0.01$), and multiple comparisons using the Tukey method revealed significant regional differences (Figure 3). An average difference of approximately 2 [°C] was observed between Osaka and Toyooka, and approximately 4 [°C] between Toyooka and Yonezawa. Thus, for subsequent analysis, Osaka and Toyooka were included in the Kinki region because of their geographical proximity.

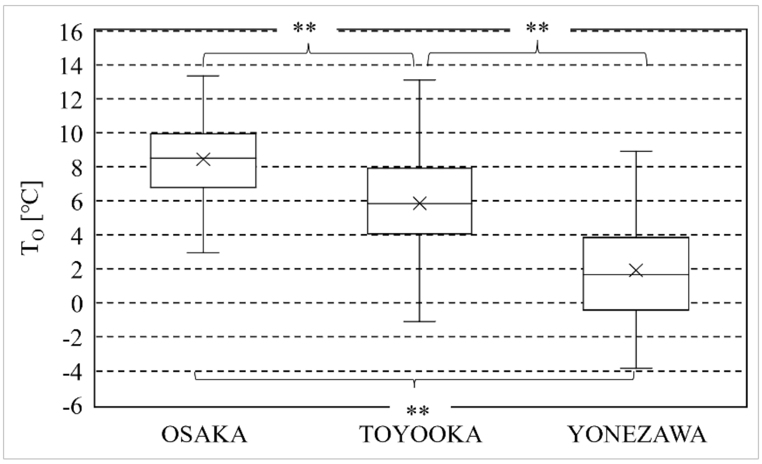


Figure 3: Average Daytime Outdoor Temperatures During the Measurement Period, **: P< 0.01

The box plot shows the data distribution for the To [°C]. The box represents the interquartile range from the first quartile to the third quartile, with the line inside the box indicating the median. The whiskers extend to the minimum and maximum values. The × symbol represents the mean.

Figures 4 and 5 present box plots of the operative temperature OT $_{Ave}$ and SHR for participants grouped into the Kinki and Yonezawa regions, respectively. The Shapiro–Wilk test indicated that the data for OT $_{Ave}$ did not follow a normal distribution. Because the average values for each participant could be considered independent samples, regional differences were assessed using the Mann–Whitney U test. The results demonstrated that OT $_{Ave}$ was significantly higher in the Kinki region, with an average difference of about 3.5 [°C].

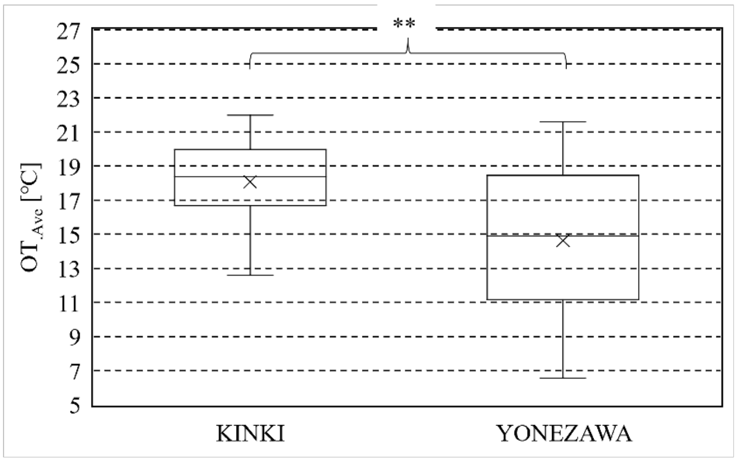


Figure 4: Differences in Average Operative Temperature During Sleep by Region, **: P< 0.01

The box plot shows the data distribution for the $OT_{,Ave}$ [°C]. The box represents the interquartile range from the first quartile to the third quartile, with the line inside the box indicating the median. The whiskers extend to the minimum and maximum values. The × symbol represents the mean.

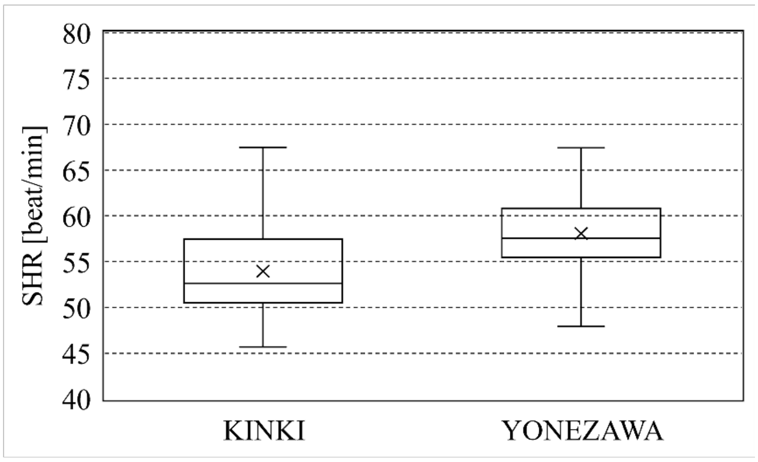


Figure 5: Differences in SHR by Region

The box plot shows the data distribution for the SHR [beat/min]. The box represents the interquartile range from the first quartile to the third quartile, with the line inside the box indicating the median. The whiskers extend to the minimum and maximum values. The × symbol represents the mean.

SHR was analyzed using a mixed-effects model, as it does not involve repeated measures that are equally spaced and time-dependent. A robust estimation was performed because the residuals of the SHR did not exhibit normality. The fixed effect was the region and the random effect was the participant. Bootstrap resampling was performed 1000 times to obtain a 95% confidence interval. The results shown in Table 7 indicate that the bias due to resampling is small relative to the estimated value, and the SHR differed by 4.11 [beats/min] between the regions. This result was significant because the 95% confidence interval fell entirely within the positive range.

3.3 Relationship Between Bedroom Environment and SHR

Table 8 shows the Spearman rank correlation coefficients between SHR and each environmental factor. The "Meta" column represents the pooled correlation coefficient obtained through meta-analysis based on the correlation coefficients and sample sizes of all participants. The "All" column represents the correlation calculated from the raw data of all participants. The pooled correlation coefficient indicated significant correlations between BM and $CO_{2\,Ave}$, and Duration had a P value of 0.05. For $CO_{2\,Ave}$, all participants showed positive correlation coefficients; BM had positive correlation coefficients for all participants except A2, and Duration had a positive correlation for all participants except A8. The raw data of all participants, all factors except Lx_{Ave} showed significant correlations.

A separate analysis of BM revealed no correlation with other environmental factors. Therefore, it is considered that there are no confounding variables affecting both SHR and BM. Additionally, similar to the results from previous reports in this series [4], no mediating variables influencing BM were identified.

Next, a mixed-effects model was used to confirm the linear correlation between the SHR and each environmental factor. Robust estimation was performed, as described in the previous section. The fixed effect was the regression line slope and the random effect was participant-specific variability. The results are summarized in Table 9. The pooled regression coefficients for the linear regression indicated significant correlations with BM, Ta_{Ave}, Tr_{Ave}, OT_{Ave}, Tb_{Ave}, and $CO_{2\,Ave}$., where OT_{Ave} is a value calculated from Ta_{Ave} and Tr_{Ave}. Based on the results in Tables 8 and 9, we will focus on BM, OT_{Ave}, Tb_{Ave}, and $CO_{2\,Ave}$ for further analysis.

A robust mixed-effects model with SHR as the dependent variable was used to determine the optimal model. Table 10 shows the examined models, along with the coefficients and P values of the variables. The interaction terms between variables are indicated by ":". Due to the robustness of the model, goodness-of-fit indices could not be calculated. In Model 3, the interaction term between OT_{Ave} and Tb_{Ave} was significant, whereas in Model 8, the interaction term between Tb_{Ave} and $CO_{2\,Ave}$ was significant.

Table 11 shows the correlation coefficients between the average SHR values for each participant during the measurement period and the average values of each environmental factor in the bedrooms of the participants during the measurement period. Significant negative correlations were observed for Ta_{Ave}, Tr_{Ave}, and OT_{Ave}; consistent with the results in Figure 5 and Table 7, lower temperatures corresponded to higher SHR.

To account for the average OT_{Ave} during the entire measurement period of each participant, a multilevel structural equation model was examined. Table 12 shows the examined models, posterior predictive P-values, and DIC. The intraclass correlation coefficient (Note 5) for the similarity between SHR and OT_{Ave} was calculated and found to be significant ($P<0.01$), exceeding 0.1, with a design effect (Note 5) >2. The average OT_{Ave} of each participant during the entire measurement period was considered 'between' levels, and the deviations from these averages on each measurement day were considered 'within' levels. The dependent variable was SHR, and the explanatory variables were BM, Tb_{Ave}, OT_{Ave}, and $CO_{2\,Ave}$. Assuming non-parametric distributions for the obtained values, Bayesian estimation using the MCMC method was performed. The analysis was conducted using Mplus Version 8.4 with eight Markov chains and 49,000 MCMC simulation runs. The model with the highest posterior predictive P-value and the smallest DIC was Model F, indicating no significant correlation 'between' levels of the average OT_{Ave}. This may be attributed to the small number of participants (n=9). In the model similar to Model 3 in Table 10, the posterior predictive P-values are 0. The interaction between Tb_{Ave} and $CO_{2\,Ave}$ was significant in Model F, and a similar result was obtained in Model 8. Based on these findings, Models 8 and F, which included BM, Tb_{Ave}, OT_{Ave}, $CO_{2\,Ave}$, and the interaction term between Tb_{Ave}, and $CO_{2\,Ave}$, were adopted as the best-fit models.

Table 13 shows the coefficients of each variable in Model F from Table 12 along with the standardized coefficients. When standardized, the interaction term between Tb_{Ave}, and $CO_{2\,Ave}$ had the highest negative coefficient. Similar to Model 8, the signs for Tb_{Ave}, and OT_{Ave} are reversed.

4. Discussion

Regarding Sleep Duration, Table 8 shows a negative correlation for all participants except for A8, and Table 9 shows a negative correlation. However, this difference was not significant. Although a tendency for SHR to increase as sleep duration decreases was observed, further investigation is needed.

For BM, Table 8 shows a positive correlation for all participants, except for A2, with a significant pooled correlation coefficient. Similarly, Table 9 indicates a significant positive correlation, and Models 8 in Table 10 and F in Table 12 have significant coefficients. No significant correlations were observed among the participants (Table 11). It is clear that higher frequencies of body movement, including turning over, increase heart rate. However, the correlation between BM and SHR was not consistent across all participants.

Regarding the daytime outdoor temperature To, Table 8 shows significant correlations for some participants; however, the direction (positive or negative) was inconsistent. The directions varied even for participants without significant correlations. Table 11 also shows no significant correlations. Therefore, the effect of outdoor temperature on SHR is unclear. Similar to earlier findings [10], To was unlikely to affect SHR, and SHR was more likely influenced by temperatures close to the measurement time.

Tables 9 and 11 show significant negative correlations for Ta_{Ave}, Tr_{Ave}, and OT_{Ave} within and between participants, and Model F in Table 13 shows a negative correlation with OT_{Ave}, indicating a decrease of approximately 0.4 [beats/min] for each 1 [°C] change. Earlier summer measurements [10, 11] demonstrated positive correlations, indicating the opposite relationship. During winter, different autonomic thermoregulatory mechanisms are in play compared with summer, involving non-shivering and shivering thermogenesis to regulate body temperature in response to cold [12]. Although body exposure is lower in winter than in summer, Tsuzuki et al. [13] reported that diurnal fluctuations in rectal temperature correlate more strongly with the skin temperature of exposed areas, such as the forehead, than with bed microclimate temperature. They found that core body temperature drops >0.7 [°C] in a 17 [°C] sleeping environment, with even greater drops in lower temperature conditions. The same may apply to day-to-day fluctuations where the operative temperature around the head significantly affects the core body temperature. Non-shivering thermogenesis metabolism occurs with a decrease of <0.6 [°C] from the neutral zone of core body temperature, with metabolic rate inversely proportional to core body temperature [14, 15]. This increase in average nocturnal metabolism likely contributed to the increase in SHR. Significant negative correlations were observed for the Ta_{Ave}, Tr_{Ave}, and OT_{Ave} (Table 11). As shown in Figure 4 and Table 7, participants with a higher OT_{Ave} have a lower SHR, indicating that maintaining higher room temperatures during sleep could potentially reduce SHR.

Regarding the bed microclimate temperature Tb_{Ave}, significant positive correlations were found, as shown in Table 9, Model 8 in Table 10, and Model F in Table 13. Models 8 and F had opposite signs for Tb_{Ave} and OT_{Ave}, leading to the consideration that while OT_{Ave} affects the core body temperature through respiration, Tb_{Ave} directly affects the skin surface of the body. Higher skin surface temperatures cause vasodilation and increased blood flow [16, 17], which likely increases the heart rate. When the skin is less affected by the indoor temperature due to being covered by the duvet, the body temperature likely causes the SHR to stabilize at a higher level. In Model 8, a 1 [°C] change corresponded to approximately a 0.6 [beats/min] change, and in Model F, a 1 [°C] change corresponded to approximately a 0.5 [beats/min] change, indicating larger unit fluctuations than OT_{Ave}. Table 9 shows a coefficient of approximately 0.2 [beats/min] for Tb_{Ave}. This lower value compared with the models was likely due to not accounting for the influence of other factors.

The $CO_{2\,Ave}$ showed significant positive correlations with all participants, with a significant pooled correlation coefficient (Table 8). Significant positive slopes are also observed in Table 9, Model 8 in Table 10, and Model F in Table 13. Azuma et al. [18] reported clear linear physiological changes at indoor carbon dioxide concentrations above 500 [ppm], with the heart rate increasing with higher carbon dioxide levels, which is consistent with the present results. This correlation was not observed in earlier summer studies [10, 11], suggesting a different response in summer and winter. In Model 8, a 100 [ppm] change corresponded to approximately a 2.2 [beats/min] change, and in Model F, a 100 [ppm] change corresponded to approximately a 1.9 [beats/min] change. Table 9 shows a coefficient of approximately 0.4 [beats/min] for a 100 [ppm] change in $CO_{2\,Ave}$. This lower value compared with the models was likely due to not accounting for the influence of other factors. These findings are consistent with those of MacNaughton et al. [19], who reported an increase in heart rate of 2.3 [bpm] with a 1000 [ppm] increase in carbon dioxide concentration. Although the coefficients in Table 9 may reflect the actual living fluctuations more accurately, controlled laboratory experiments could show variations similar to those in the models. The correlation for average $CO_{2\,Ave}$ during the measurement period was not significant among participants (Table 11). Azuma et al. [18] reported differences in responses to short- and long-term carbon dioxide exposure, suggesting that the lack of an apparent effect on the average $CO_{2\,Ave}$ during the measurement period may be due to acclimatization to long-term conditions, with deviations from these long-term conditions affecting SHR. Additionally, the significant interaction term between Tb_{Ave} and $CO_{2\,Ave}$ in Model 8 in Table 10 and Model F in Table 13 indicates that higher bed microclimate temperatures reduce the impact of carbon dioxide concentration on SHR. This could explain why the lack of correlation was observed in summer, as higher temperatures make it harder for carbon dioxide levels to affect SHR. However, the underlying mechanism requires further investigation.

Relative humidity Hc_{Ave} showed no significant correlation (Table 8), with inconsistent slopes, regardless of high or low humidity. No significant correlation was observed between the average Hc_{Ave} across all nights and average SHR (Table 11). Although low humidity can affect the skin and mucous membranes, causing discomfort, such as pain and itching [20–22], no apparent trends were observed within the range of measurements in this study.

Illuminance Lx_{Ave} shows no significant correlation with inconsistent positive and negative slopes, as shown in Table 8. Although a relatively high illuminance was observed for A3 and A4 on certain nights (Figure 2), no significant correlations were found for these participants. This is consistent with earlier findings [4, 10–11], indicating no significant impact of Lx_{Ave} on SHR.

In conclusion, for male participants in winter, significant linear correlations were found between SHR and room, radiant, and bed microclimate temperatures, and carbon dioxide concentration, with the strongest linear correlation observed for BM. Higher average bedroom temperatures during sleep were associated with lower average SHR, suggesting that maintaining a consistently high operative temperature and reducing daily fluctuations can help reduce SHR. Improving bedroom insulation rather than relying solely on heating devices is important for temperature regulation during the heating season. Additionally, reducing carbon dioxide concentrations could help lower SHR, emphasizing the importance of maintaining good ventilation.

5. Limitations of the Study

The present results pertain to healthy males in their twenties residing in temperate regions, with an average BMI. Based on these findings and previous the study [10], it can be concluded that the $CO_{2\ Ave}$ and OT_{Ave} have a significant impact on SHR in this demographic. However, it is not possible to generalize these results to populations outside of the studied range. Furthermore, this study was limited to typical bedroom environments during winter and did not address extremely cold conditions or other seasons. Because this was an observational study, it is important to verify whether similar results could be obtained through intervention studies.

6. Conclusion

In this study, experiments were conducted in participants' usual bedrooms during winter to investigate the environmental factors influencing SHR. The findings were as follows:

-Similar to the summer season, daytime outdoor temperature had no effect on SHR.
-Linear evaluation showed a significant negative correlation between average SHR and average OT_{Ave} during the measurement period, with a slope of approximately 0.9 [beats/min] for each 1 [°C] decrease.
-Within the measured range, no apparent correlation was observed between the SHR and relative humidity or illuminance.
-The model with SHR as the dependent variable showed that the most explanatory models included BM, $CO_{2\ Ave}$, Tb_{Ave}, OT_{Ave}, and the interaction term between Tb_{Ave} and $CO_{2\ Ave}$. OT_{Ave} and the interaction term between Tb_{Ave} and $CO_{2\ Ave}$ have significant negative coefficients, whereas the other variables have significant positive coefficients.
Based on these findings, it is evident that the SHR increases as the temperature decreases during winter, whereas in an earlier study in this series, the SHR increases as the temperature increases during summer. This suggests the existence of an optimal temperature range for the lowest SHR throughout the year. The next report in this series will examine annual variations, including intermediate seasons, to determine optimal bedroom environments.

Glossary

Ta: Room temperature [°C]

Hc: Room relative humidity [%]

Tr: Indoor radiant temperature [°C]

Tb: Bed microclimate temperature [°C]

CO_2: Carbon dioxide concentration around the head area [ppm]

Lx: Illuminance around the head area [lx]

OT: Operative temperature [°C]

In this study, because the bedroom shapes and window proportions vary for each participant, the convective heat transfer coefficient (α_a) and the radiative heat transfer coefficient (α_r) are defined as follows.

$\alpha_a = \alpha_r$

The calculation formula for OT_{Ave} is as follows:

$OT_{Ave} = (\alpha_a * Ta_{Ave} + \alpha_r * Tr_{Ave}) / (\alpha_a + \alpha_r)$

When the wind speed is <0.2 [m/s]:

Thus,

$OT_{Ave} = (Ta_{Ave} + Tr_{Ave}) / 2$

To: Daytime outdoor temperature [°C]

Footnotes

1. This paper is submitted concurrently with [4], which is under review.
2. The participant experiments were conducted in accordance with the methods approved by the Yamagata University Faculty of Engineering Research Ethics Committee in 2021. An explanatory document and consent form based on ethical guidelines were prepared, and informed consent was obtained.
3. A preliminary measurement conducted in A1's bedroom revealed that the direct airflow from a fan or air conditioner exceeded 0.2 [m/s]. In comparison, the airflow did not exceed 0.2 [m/s] when the air conditioner was not blowing directly.
4. In the pre-sleep questionnaire, to identify psychological, social, physical, and chemical stress factors, and daily activities that might affect physiological measurements, the following items were asked:
   - Physical stress factors include daytime outdoor heat/cold temperature, heat/cold temperature during work or study, daytime noise levels, subjective daytime barometric pressure changes, and humidity perceptions.
   - Physiological stress factors: presence of exercise, duration of exercise, presence of naps, duration of naps, presence of bathing, bathing method, duration and time of bathing, and eye strain.
   - Other factors include the length of study or work hours, difficulty of study or work, duration of smartphone use, duration of driving, amount of food intake, caffeine intake, alcohol consumption, smoking, presence and type of medication, subjective effects of pollen or yellow dust, subjective symptoms, clothing, and bedding type.

   In the wake-up questionnaire, the following items were asked:
   - Sleep and wake times, presence of presleep exercise, wake-up method, clothing, bedding, use of cooling devices, activities during awakening, and any issues during sleep.
5. The intraclass correlation coefficient (ICC) is the ratio of the variance at the group level to the total variance and is calculated using the following formula, which is an indicator of within-group similarity. If similarity is confirmed, the data should be treated hierarchically.

   $ICC = (MS_B - MS_w) / (MS_B + (k' - 1) MS_W)$

   MS_B: Mean Square Between groups

= Sum of Squares Between groups/degrees of freedom for a factor

MS_{W}: Mean Square Within groups

= Sum of Squares Within groups/degrees of freedom for an error

K' : Average number of data points within groups

The design effect (DE) is calculated as follows:

DE = 1 + (K'- 1) ICC

Similarity is determined in any of the following cases:

1. ICC is significant
2. ICC exceeds 0.1
3. DE is 2 or more

References

[1] C.D. Johansen, R.H. Olsen, L.R. Pedersen, P. Kumarathurai, M.R. Mouridsen, Z. Binici, T. Intzilakis, L. Kober, A. Sajadieh, Resting, night-time, and 24 h heart rate as markers of cardiovascular risk in middle-aged and elderly men and women with no apparent heart disease, Eur. Heart J. 34, 23 (2013) 1732–1739. https://doi.org/10.1093/eurheartj/ehs449.

[2] C.-L. Wang, Y.-H. Chan, H.-F. Lee, F.-C. Hsiao, P.-H. Chu, High nighttime heart rate is associated with increased risk of all-cause mortality in patients with heart failure and reduced ejection fraction, Int. Heart J. 61, 2 (2020) 289–294. https://doi.org/10.1536/ihj.19-403.

[3] B.O. Hartaigh, M. Gaksch, K. Kienreich, M.R. Grubler, N. Verheyen, W. Marz, A. Tomaschitz, T.M. Gill, S. Pilz, Associations of daytime, nighttime, and 24-hour heart rate with four distinct markers of inflammation in hypertensive patients: the Styrian Hypertension Study, J. Clin. Hypertens. (Greenwich) 16, 12 (2014) 856–861. https://doi.org/10.1111/jch.12420.

[4] N. Oota, Y. Yamauchi, G. Iwase, M. Abuku, Y. Hiraguri, Effects of bedroom environment on average heart rate during sleep in temperate regions: Part I - Summer conditions in healthy males in their twenties with average BMI, unpublished results.

[5] L. Madaniyazi, Y. Zhou, S. Li, G. Williams, J.J.K. Jaakkola, X. Liang, Y. Liu, S. Wu, Y. Guo, 2016. Outdoor temperature, heart rate and blood pressure in Chinese adults: Effect modification by individual characteristics, Sci. Rep. 6, 21003. https://doi.org/10.1038/srep21003.

[6] G. Quer, P. Gouda, M. Galarnyk, E. Topol, S.R. Steinhubl, 2020. Inter- and intraindividual variability in daily resting heart rate and its associations with age, sex, sleep, BMI, and time of year: Retrospective, longitudinal cohort study of 92,457 adults, PLoS One, 15, 2, e0227709. https://doi.org/10.1371/journal.pone.0227709.

[7] N. Oota, A. Iwamae, F. Kimura, M. Abuku, H. Hiraguri, Effects of environmental factors, subject's body motion, and heart rate variability on subjective feeling of sleep, J. Environ. Eng. AIJ. 85, 778 (2020) 923–933. https://doi.org/10.3130/aije.85.923.

[8] N. Oota, Y. Yamauchi, M. Abuku, Y. Hiraguri, Measurement and analytics method for daily differences variation and seasonal variation for the association between bedroom environment and heart rate during sleep, and identification of the number of repeated measurements, Transactions of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, 322, (2024) 23–30.

[9] Ministry of Land, Infrastructure, Transport and Tourism/Japan Meteorological Agency. https://www.data.jma.go.jp/obd/stats/etrn/index.php (accessed 24 April 2024).

[10] N. Oota, Y. Yamauchi, G. Iwase, M. Abuku, Y. Hiraguri, Effects of thermal environment in winter on average heart rate during sleep, J. Hum. and Living Environ. 31, 1 (2024) 23–32.

[11] N. Oota, Y. Yamauchi, G. Iwase, M. Abuku, Y. Hiraguri, Effects of thermal environment in summer on average heart rate during sleep, J. Hum. and Living Environ., 31, 1 (2024) 1–9.

[12] Kazuyuki Kanoosue, Toshihiro Nakajima, Nouto Taion- Shonetsu/ Kanrei Kankyo tono Tatakai, Kyoritsu Shuppan Co., Ltd., Tokyo, 2000.

[13] K. Tsuzuki, K. Okamoto-Mizuno, K. Mizuno, The effects of low air temperatures on thermoregulation and sleep of young men while sleeping using bedding, Buildings, 8(6), 76 (2018). https://doi.org/10.3390/buildings8060076.
[14] I.B. Mekjavi, C.J. Sundberg, D. Linnarsson, Core temperature "null zone", J. Appl. Physiol. 71, 4 (1985) 1289–1295. https://doi.org/1289/1295, 10.1152/jappl.1991.71.4.1289.
[15] D.I. Sessler, Perianesthetic thermoregulation and heat balance in humans, FASEB Journal, 7, 8 (1993) 638–644. https://doi.org/10.1096/fasebj.7.8.8500688.
[16] C.G. Crandall, T.E. Wilson, Human cardiovascular responses to passive heat stress, Compr. Physiol. 5, 1 (2016) 17–43. https://doi.org/10.1002/cphy.c140015.
[17] T.-H. Chou, E.F. Coyle, Cardiovascular responses to hot skin at rest and during exercise, Temperature (Austin), 10, 3 (2023) 326–357. https://doi.org/10.1080/23328940.2022.2109931.
[18] K. Azuma, N. Kagi, U. Yanagi, H. Osawa, Effects of low-level inhalation exposure to carbon dioxide in indoor environments: A short review on human health and psychomotor performance, Environ. International 121, 1 (2018) 51–56. https://doi.org/10.1016/j.envint.2018.08.059.
[19] P. MacNaughton, J. Spengler, J. Vallarino, S. Santanam, U. Satish, J. Allen, Environmental perceptions and health before and after relocation to a green building, Build. and Environ. 104 (2016) 138–144. https://doi.org/10.1016/j.buildenv.2016.05.011.
[20] N.L. Nagda, M. Hodgson, Low relative humidity and aircraft cabin air quality, Indoor Air, 11, 3 (2001) 200–214. https://doi.org/10.1034/j.1600-0668.2001.011003200.x.
[21] ASHRAE 2010. Thermal Environmental Conditions for Human Occupancy, ANSI/ASHRAE Standard 55-2010, 7.
[22] S. Takada, Fundamental study on sensation of dryness and indoor thermal environmental conditions, J. Environ. Eng. AIJ. 78, 693 (2013) 835–840. https://doi.org/10.3130/aije.78.835.

Table 1: Participant Attributes and Measurement Periods

Participant ID	Sex	Age	BMI	Daytime Location And Bedroom Location	Measurement Period	Number of Data Points
A1	Male	21	20.2	Higashi Osaka City	Jan 10–Feb 7, 2023	21
A2		21	25.5		Feb 8–Feb 27, 2023	15
A3		21	19.0	Toyooka City	Dec 1, 2022–Jan 8, 2023	22
A4		21	20.1	Higashi Osaka City	Dec 1–Dec 22, 2023	18
A5		22	21.0	Yonezawa City	Jan 8–Feb 7, 2023	25
A6		21	19.4		Feb 8–Mar 4, 2023 Jan 16–Feb 6, 2024	23 22
A7		21	17.5		Dec 6–Dec 28, 2022 Dec 5, 2023–Jan 15, 2024	22 25
A8		22	19.8		Dec 1–Dec 26, 2023	18
A9		22	21.3		Dec 28–Dec 19, 2023	24

Table 2: Measured Parameters

Physiological Measures	Body Movement, Heart Rate, Respiratory Rate
Environmental Factors	① Environmental Factors
	② Room Temperature [°C], Room Relative Humidity [%], Illuminance Around the Head Area [lx]
	③ Radiant Temperature Around the Head Area [°C]
	④ Bed Microclimate Temperature [°C]

Table 3: Amount of Clothing Worn During Sleep

Participant ID	A1	A2	A3	A4	A5
CLO Value	0.59±0.03	0.60±0	0.60±0	0.55±0.01	0.55±0
Participant ID	A6	A7	A8	A9	-
CLO Value	0.55±0	0.60±0	0.55±0	0.55±0	-

Table 4: Average Bedtime and Total Sleep Time

Values in parentheses represent the standard deviation in minutes.

	A1	A2	A3	A4	A5
Bedtime (hh:mm)	2:53(84)	0:06(58)	3:13(106)	5:17(193)	1:29(90)
Total Sleep Time (hh:mm)	5:24(62)	6:15(63)	8:05(153)	6:15(69)	7:11(90)
	A6	A7	A8	A9	-
Bedtime (hh:mm)	0:42(38)	3:53(96)	2:41(125)	5:19(125)	-
Total Sleep Time (hh:mm)	7:38(40)	6:24(67)	6:41(82)	6:51(126)	-

Table 5: Number of Days Using Air Conditioning

Participant ID	A1	A2	A3	A4	A5
Air Conditioning	15	15	22	0	0
Participant ID	A6	A7	A8	A9	-
Air Conditioning	39	0	0	24	-

Table 6: Number of Days Using Bed Duvet

Participant ID	A1	A2	A3	A4	A5
Blanket	16	0	22	16	24
Towel Blanke	0	0	0	0	0
Down Duvet	5	15	0	19	24
Electric Blanket	0	0	0	0	24
Participant ID	A6	A7	A8	A9	-
Blanket	43	0	0	24	-
Towel Blanke	45	0	0	0	
Down Duvet	0	47	18	24	
Electric Blanket	0	0	0	0	-

Table 7: Estimated Fixed Effects of Regional Differences Using a Robust Mixed-Effects Model with SHR as the Dependent Variable

The reference level of the region is Yonezawa.

	Estimate Standard Error	Bias	95% C.I
Intercept	53.64 0.56	0.035	-
Region (Kinki)	4.11 0.62	-0.034	2.82 5.23

Table 8: Spearman Rank Correlation Coefficients Between SHR and Environmental Factors

***: P<0.001 **: P<0.01 *: P<0.05 +: P<0.1

All: the correlation calculated from the raw data of all participants

Meta: the pooled correlation coefficient obtained through meta-analysis

r: correlation coefficient

N: number of samples

Participant		Duration	BM	To	Ta_{Ave}	Tr_{Ave}	OT_{Ave}	Tb_{Ave}	$CO_{2\,Ave}$	Hc_{Ave}	Lx_{Ave}
All	r	-0.13*	0.23**	-0.28**	-0.56**	-0.61**	-0.60**	0.30**	0.25**	0.24**	0.10
	N	235	235	235	235	235	228	235	235	235	235
A1	r	-0.06	0.11	0.29	-0.24	-0.41	-0.45	-0.30	0.35	0.49	0.08
	N	21	21	21	21	32	17	21	21	21	21
A2	r	-0.24	-0.43	0.09	0.10	0.12	0.03	0.43	0.36	-0.05	0.15
	N	15	15	15	15	15	15	15	15	15	15
A3	rr	-0.18	0.29	-0.46*	-0.19	-0.26	-0.29	-0.15	0.23	-0.35	0.14
	N	22	22	22	22	22	20	22	22	22	22
A4	r	-0.25	0.26	0.17	0.29	0.36	0.32	0.53*	0.11	0.35	0.18
	N	18	18	18	18	18	18	18	18	18	18
A5	r	-0.25	0.33	0.44*	0.39	0.47*	0.43*	-0.18	0.12	0.13	0.20
	N	25	25	25	25	25	25	25	25	25	25
A6	r	-0.07	0.34	-0.31	-0.06	0.01	-0.02	0.14	0.15	0.12	0.26
	N	45	45	45	45	45	44	45	45	45	45
A7	r	-0.20	0.39**	-0.35*	-0.16	-0.15	-0.16	-0.11	0.09	-0.18	-0.02
	N	47	47	47	47	47	47	47	47	47	47
A8	r	0.16	0.31	-0.13	-0.09	-0.15	-0.09	-0.57*	0.29	-0.04	-0.26
	N	18	18	18	18	18	18	18	18	18	18
A9	r	-0.09	0.39	0.10	0.19	0.34	0.26	0.66**	0.75**	-0.15	-0.12
	N	24	18	24	24	24	24	24	24	24	24
Meta		-0.14+	0.28***	-0.04	0	0.02	0.01	0.06	0.28**	0.03	0.08

Table 9: Estimated Fixed Effects of Linear Regression Coefficients Using a Robust Mixed-Effects Model with SHR as the Dependent Variable and One Explanatory Variable

***: P<0.001 **: P<0.01 *: P<0.05 +: P<0.1, Estimate: regression coefficient

	Duration	BM	T_o	Ta_{Ave}	Tr_{Ave}	OT_{Ave}	Tb_{Ave}	$CO_{2\,Ave}$	Hc_{Ave}
Estimate	-6.42+	12.92***	-0.05	-0.30**	-0.31**	-0.33**	0.17**	0.0044**	0.04

Table 10: Estimated Fixed Effects of Linear Regression Coefficients Using a Robust Mixed-Effects Model with SHR as the Dependent Variable and Multiple Explanatory Variables

***: P<0.001 **: P<0.01 *: P<0.05 +: P<0.1

Variables separated by a colon (:) represent interaction terms

The numbers in the table are regression coefficients

	Intercept	BM	OT_{Ave}	Tb_{Ave}	$CO_{2\,Ave}$	OT_{Ave}: Tb_{Ave}	BM: OT_{Ave}	OT_{Ave}: $CO_{2\,Ave}$	BM: Tb_{Ave}	BM: $CO_{2\,Ave}$	Tb_{Ave}: $CO_{2\,Ave}$
Model 1	48.89***	12.82***	-0.16	0.13*	0.0033*	-	-	-	-	-	-
Model 2	46.58***	13.57***	-	0.12*	0.0031*	-	-	-	-	-	-
Model 3	72.58***	11.76***	-1.43*	-0.66*	0.0035*	0.04*	-	-	-	-	-
Model 4	48.22***	14.59	-0.12	0.14*	0.0033*	-	-0.12	-	-	-	-
Model 5	46.59***	12.99***	-0.02	0.13*	0.0061	-	-	-0.0002	-	-	-
Model 6	50.49***	7.07	-0.15	0.07	0.0032*	-	-	-	0.23	-	-
Model 7	49.70***	10.06	-0.16	0.13*	0.0023	-	-	-	-	0.0040	-

Model 8	34.69***	12.63***	-0.18	0.63**	0.0222**	-	-	-	-	-	-0.0006*

Table 11: Correlation Between Participants for Average SHR and Environmental Factors Calculated Over the Measurement Period for Each Participant

***: P<0.001 **: P<0.01 *: P<0.05 +: P<0.1

r: correlation coefficient

	Duration	BM	To	Ta_{Ave}	Tr_{Ave}	OT_{Ave}	Tb_{Ave}	$CO_{2\,Ave}$	Hc_{Ave}
r	-0.17	-0.04	-0.50	-0.83**	-0.91***	-0.88**	0.60	0.25	0.43

Table 12: Results of Multilevel Structural Equation Modeling with SHR as the Dependent Variable

***: P<0.001 **: P<0.01 *: P<0.05 +: P<0.1

Variables separated by a colon (:) represent interaction terms

	Level	Model	Posterior Predictive P-Value	DIC
Model A	Within	SHR～BM**+ $CO_{2\,Ave}$ *+ Tb_{Ave} *+ OT_{Ave} *+ Tb_{Ave}: $CO_{2\,Ave}$ *	0.293	2027.099
	Between	avgSHR~avgOT+		
Model B	Within	SHR～BM**+ $CO_{2\,Ave}$ *+ Tb_{Ave} + OT_{Ave} *	0.298	2032.270
	Between	avgSHR~ avgOT+		
Model C	Within	SHR～BM**+ $CO_{2\,Ave}$ *+ OT_{Ave}	0.333	2414.273
	Between	avgSHR~ avgOT+		
Model D	Within	SHR～BM**+ $CO_{2\,Ave}$ *	0.367	2412.651
	Between	avgSHR~avgOT+		
Model E	Within	SHR～BM**+ $CO_{2\,Ave}$ *+ OT_{Ave} *	0.434	1227.432
Model F	Within	SHR～BM**+ $CO2_{Ave}$*+ Tb_{Ave}*+ OT_{Ave} **+ Tb_{Ave}: $CO_{2\,Ave}$ *	0.445	1149.409

Table 13: Correlation Between Participants for Average SHR and Environmental Factors Calculated Over the Measurement Period for Each Participant

***: P<0.001 **: P<0.01 *: P<0.05 +: P<0.1

Variables separated by a colon (:) represent interaction terms

	BM	OT_{Ave}	Tb_{Ave}	$CO_{2\,Ave}$	Tb_{Ave}: $CO_{2\,Ave}$
Model F	10.88**	-0.38**	0.51*	0.019*	-0.0005*
Model F Standardized	0.23**	-0.34**	0.68*	0.93*	-1.12*