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

Abstract: The average heart rate at night is an important biomarker and environmental factors in the bedroom may affect the heart rate during sleep. There is limited research on the relationship between average heart rate during sleep and indoor environmental factors. Therefore, this paper presents an experiment designed to identify the environmental factors in the bedroom that affect variations in sleep average heart rate (SHR [1]). Measurements were conducted on three male participants in their usual sleeping environments over two periods: during two summers from July 5 to September 22, 2022; and from August 9 to September 30, 2023. The experimental conditions were kept constant during both periods. The field survey did not impose any specific conditions on participants. Heart rate and body movement were measured along with environmental factors, such as thermal environment, humidity, illuminance, and CO_2 concentration. The results demonstrated that the thermal environment had the strongest linear correlation with SHR. In particular, room, radiant, and operative temperatures all showed a significant positive correlation. The average operative temperature and average heart rate over the entire experimental period for each participant showed a significant positive correlation with a coefficient of approximately 0.38. For the bed microclimate temperature was not a mediating variable for operative temperature. No confounding effects between SHR and body movement due to operative temperature were found. On the above, the multilevel structural equation model identified operative temperature and body movement as the variables that best explained SHR. Overall, a greater understanding of how environmental conditions affect sleep heart rate could enable the design of environments that promote a stable heart rate during sleep.

Keywords: Average heart rate during sleep, Summer, Bedroom environment, Thermal environment, Field survey.

1. Introduction

Numerous studies have utilized HRV to explore variations in heart rate during sleep [1 - 6]. HRV has demonstrated a significant correlation with the average heart rate [4, 7]. The most important indicator in HRV is the standard deviation of RR intervals, known as SDNN. The average nighttime heart rate shows a high negative correlation (r = 0.91) with the SDNN, suggesting that it could serve as a surrogate variable [1]. Sacha et al. [8] mathematically demonstrated that a lower average heart rate increases the variability of RR intervals. Long-term SDNN is indicative of autonomic nervous system activity, with higher values considered favorable [9, 10]. Based on the above, the average nighttime heart rate can serve as a surrogate for HRV, and a lower average nighttime heart

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Abbreviations

HRV: Heart rate variability index
RR: Intervals between consecutive R-waves on an electrocardiogram (ECG)
SDNN: Standard deviation of RR intervals
RHR: Resting heart rate
SHR: Average heart rate during sleep [beats/min]
BM: Body movement rate during sleep [times/min]
ipRGC: Intrinsically photosensitive Retinal Ganglion Cells
ACME: Average Causal Mediation Effects
MCMC: Markov Chain Monte Carlo
DIC: Deviance Information Criterion

rate is considered favorable for autonomic nervous system activity.

RHR, which is the number of heartbeats per minute at rest, is an important biomarker, and a high RHR is a significant predictor of mortality [11 - 16]. However, RHR measurements are typically obtained while seated and can be difficult to obtain after exercise or under stress [17, 18]. Johansen et al. [19] found that heart rate during sleep is more strongly associated with mortality than RHR and the average 24-hour heart rate. Based on the above, the average nighttime heart rate can also be regarded as an even more important biomarker than RHR.

Heart rate increases with temperature during the summer [20]. It is hypothesized that variations in SHR may be influenced by bedroom temperatures, such as room, radiant, and bed microclimate temperatures. Madaniyazi et al. [21] investigated the effects of outdoor temperature on the average heart rate among Chinese individuals. They found that heart rates increased with rising outdoor temperatures. Quer et al. [22] studied seasonal fluctuations in RHR across different seasons, finding that RHR rises with increasing outdoor temperatures and falls as temperatures decline. Previous work has shown that in hot environments, the initial average heart rate during sleep is positively correlated with the radiant temperature of the nearest partition wall [6] and that the operative temperature in the bedroom has the highest correlation with the SHR [23].

This study focused on the SHR and explored its influencing factors. Few studies focus on the relationship between SHR and the bedroom environment. Furthermore, studies on the average nighttime heart rate existing studies were conducted on large populations and did not statistically consider influencing factors, such as the indoor environment during the survey. Therefore, this study investigated the environmental factors responsible for fluctuations in SHR between nights during two summer periods. The investigation focused on room, radiant, bed microclimate, and daytime outdoor temperatures. As in Oota et al. [23], measurements were taken in a home bedroom setting close to the participants' normal sleep conditions using a non-contact/unconstrained mattress sensor to measure the heart rate in a field survey without considering specific external conditions.

In this study, three participants who could participate in the long-term survey were analyzed. These three participants are part of the eleven participants from our previous summer study [23]. The purpose of focusing on these three participants over an extended period is to obtain further results that could not be achieved in a shorter period. Additionally, by conducting long-term experiments, we aim to determine an appropriate survey period for future research.

Understanding how environmental conditions affect sleep heart rate could enable the design of environments that promote a stable heart rate during sleep.

2. Methods

2.1 Experimental Method and Measurement Factors

According to Quer et al. [22], RHR varies with age and body mass index (BMI). Additionally, According to Kanosue et al. [24], sensitivity trends differ depending on the climate of the region where people reside. Oota et al. [23] revealed that SHR in women is affected by their menstrual cycles. Experiments were conducted on three healthy male participants (A1–A3) in their twenties, each with average BMIs. All participants resided in the same temperate region of Japan as in our previous study [23] and had no sleep disorders. The experimental methods were consistent with those used in Oota et al. [23]. The experiments were conducted in the participants' home bedrooms, located in Yamagata Prefecture, Japan (Note 1). These measurements were taken from July 5 to September 22, 2022, and from August 9 to September 30, 2023.

Table 1 lists the sex, age, bedroom location, daytime location, and measurement period for each participant. The number of data points in the table represents the number of continuous overnight heart rate data points from bedtime to waking. Days with alcohol consumption, days when medication was taken, records where sleep duration was less than five hours, and any data segments with missing measurements for more than ten minutes were excluded from the data count. The physiological and environmental factors listed in Table 2 were measured in each participant's bedroom.

An example of the measurement setup for a participant's bedroom is shown in Figure 1. The measurement devices included a non-contact/unconstrained mattress sensor (aams, BioSilver Co.) to capture the body movement and heart rate continuously. Its accuracy has been confirmed in Oota et al. [6]. The sensor was placed under the mattress of the participant's bed, positioned between the participant's shoulder blades and waist. Environmental factors were measured using a TR-76Ui (T&D Co.) for measuring the CO_2 concentration in the head area; TR-74Ui (T&D Co.) for illuminance, temperature, and relative humidity in the head area; UX120-014M (ONSET Co.) for the indoor radiant temperature in the head area using a logger and thermocouple in the globe; and TR-73U (T&D Co.) for the bed microclimate temperature with a thermal sensor coated in TPE resin placed under the bed sheets.

Preliminary surveys confirmed that none of the participants used fans during sleep, and that air conditioning was not used with direct airflow. A separate preliminary measurement revealed that indoor wind speed did not exceed 0.2 [m/s] (Note 2). Therefore, wind speed measurements were not conducted during the field study. 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 3).

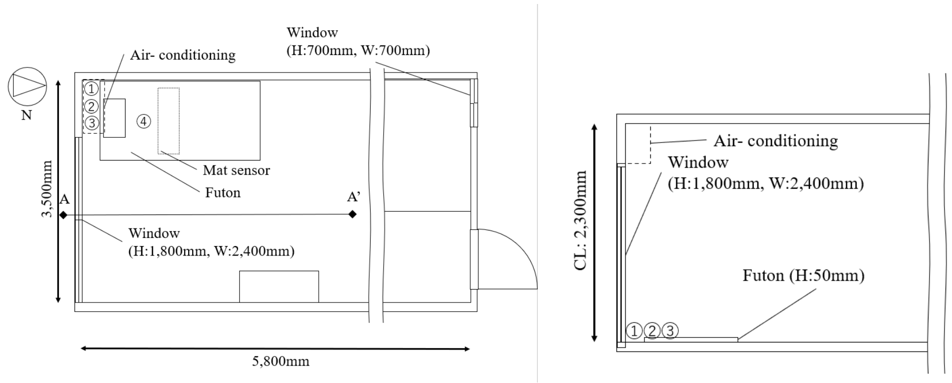


Figure 1: Example of Measurements in the Participant's Bedroom

Locations ① to ④ in the figure correspond to the positions of measurement devices for the parameters listed in Table 2.The upper figure shows the Floor Plan of Participant A1's Room.The lower figure shows the cross-sectional view of the A-A' cut section in the plan view.

2.2 Methods for Analyzing Measurement Factors

The average and standard deviation of the physiological and environmental factors were calculated each night. The calculations were as follows:

The average heart rate during sleep was calculated and designated as SHR [beats/min].

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.

Physiological measurements during sleep are typically influenced by factors such as sleep posture, bedding, and clothing. However, this study analyzed comparisons based on average values and standard deviations between several nights. It was assumed that changes in sleeping posture reflected body movements and their impact on SHR was evaluated. As shown in Table 3, there was no variation in the amount of clothing insulation between nights, which was assumed to be constant. Variations in bedding usage were interpreted as reflected in the bed microclimate temperature.

Sleep onset time was determined by the absence of body movement for 5 min starting from the self-reported bedtime noted in the waking survey, and wake-up time was determined by self-reporting. The sleep duration was calculated from these values.

OT_{Ave} was calculated using Ta_{Ave} and Tr_{Ave} (see Glossary). To (see Glossary) was based on the average meteorological data [25] from 8 AM to 5 PM in the regions where the participants spent most of their daytime. 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 shows the average and standard deviation of bedtime and total bedtime for each participant. Although there was variation in bedtime, there was no apparent reversal of day or night. Additionally, sleep habits did not change significantly over time during two summers.

Figure 2 shows the differences in To between 2022 and 2023 during the measurement period. The Mann-Whitney U test confirmed a significant difference with $P < 0.01$. The median and average temperatures in 2023 were higher by 2.3 [°C] and 1.7 [°C], respectively, compared with 2022.

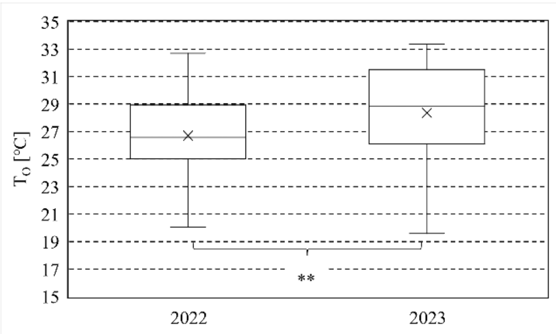
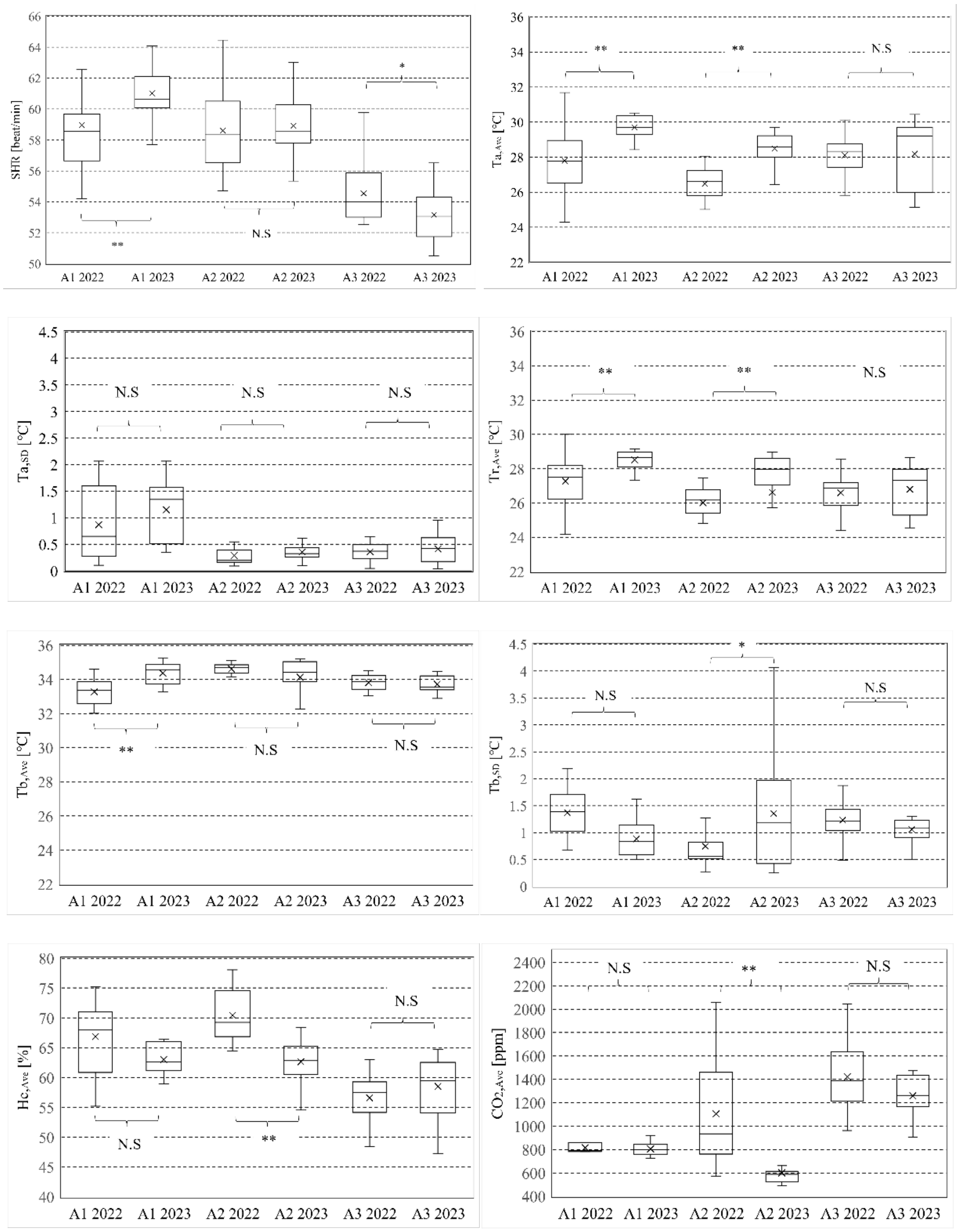


Figure 2: Average Daytime Outdoor Temperatures During the Measurement Period, **: P< 0.01. The box plot shows the data distribution for the To [°C]. The box represents the interquartile range from the first quartile to the third quartile, with the line inside the box indicating the median. The whiskers extend to the minimum and maximum values. The × symbol represents the mean.

The distributions of SHR and environmental factors 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 are shown in Figure 3.



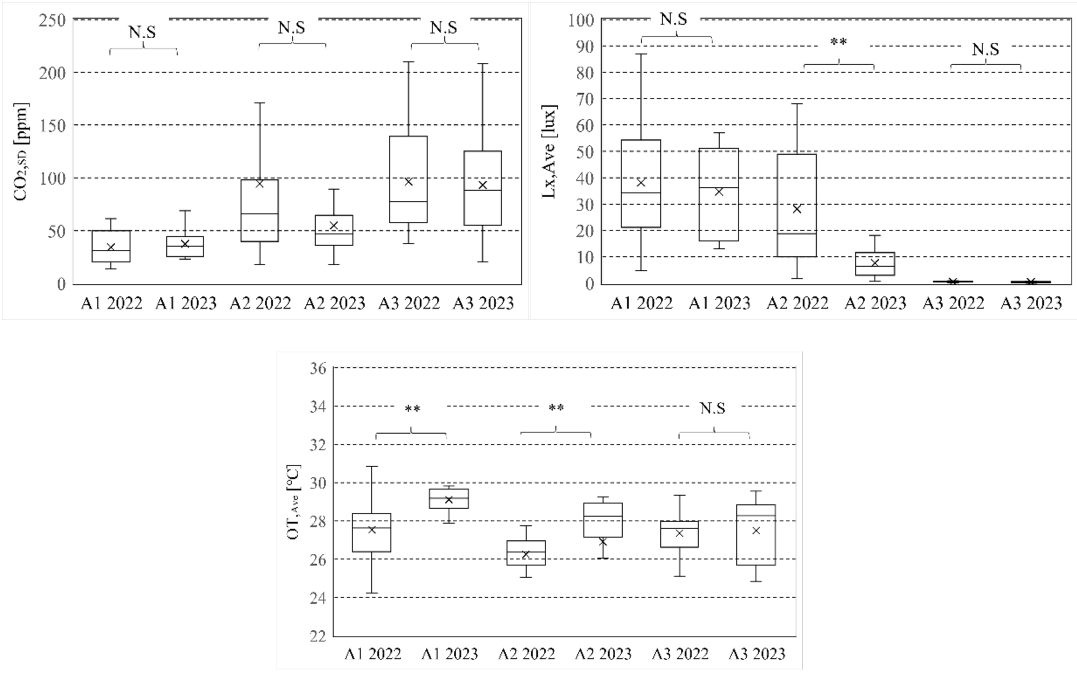


Figure 3: Measurement Results in the Participants' Bedrooms, **: P< 0.01, N.S: Not Significant

The box plot shows the distribution of the data. 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) Ta,Ave, (c) Ta,SD, (d)Tr,Ave, (e) Tb,Ave, (f) Tb,SD, (g)Hc,Ave, (h) CO2,Ave, (i) CO2,SD, (j) Lx,Ave, (k) OT,Ave

The room temperature (Ta_{Ave}) and radiant temperature (Tr_{Ave}) were higher in 2023 for participants A1 and A2, similar to the outdoor temperatures; however, no significant difference was found for participant A3. Table 5 shows that A1 and A2 did not use air conditioning and window openings were confirmed for A2, indicating susceptibility to the outdoor temperature. In contrast, A3 frequently used air conditioning, making the indoor environment relatively less affected by the outdoor temperature. This difference is likely the cause of the observed variations.

For Ta_{SD}, the day-to-day variations for A2 and A3 were within approximately 0.5 [°C]. In contrast, the day-to-day difference at A1 was more significant. This is likely because the A1's room was located on the top floor and corner of the building, with three walls facing the outside and a 4.5 [m^2] window area in a 20 [m^2] bedroom. Additionally, because A1 often slept until the daytime, as indicated in Table 4, it was considered that A1 was more susceptible to the influence of outdoor temperature.

The average bed microclimate temperature (Tb_{Ave}) exceeded the average room temperature (Ta_{Ave}), indicating the influence of body heat. Tables 3 and 6 show each participant's use of the amount of clothing worn and a bed duvet, respectively. The CLO value was consistent for all participants, with no day-to-day variation. A1, who often did not use bed duvets, was considered more susceptible to room temperature effects. However, Tb_{Ave} was not notably lower than that of the other participants. This is likely due to the consistent sleeping posture of A1. When a participant sleeps in the same bedding and nearly the same posture, the average bed microclimate temperature is determined by body and room temperatures. As the average body temperature remains constant daily, the day-to-day variation in the bed microclimate temperature is anticipated to be less than or equal to that of the room temperature. The Tb_{SD} showed more considerable day-to-day variations than the Ta_{SD}, which was likely due to changes in sleeping posture.

The average relative humidity (Hc_{Ave}) was higher for A1 and A2 in 2022, whereas A3 exhibited similar relative humidity levels in both 2022 and 2023. This could be attributed to the factors shown in Table 5: for A1 and A2, who did not use air conditioning, humidity depended on outdoor temperature, whereas for A3, who used air conditioning more frequently, humidity was somewhat controlled by the air conditioning.

Regarding carbon dioxide concentration ($CO_{2\ Ave}$), the average in A1's bedroom never exceeded 1000 [ppm], and the day-to-day variation was minimal. In contrast, in A3's bedroom, on several days the average exceeded 1000 [ppm], and the day-to-day variation was significant. This difference was likely due to the presence or absence of an operational ventilation system. In A2's bedroom, there were many days in 2022 when the average exceeded 1000 [ppm], but this was not the case in 2023, likely due to the effects of opening the windows.

In terms of illuminance (Lx_{Ave}), A1, who often woke up late (Table 4) and whose bedroom had windows on the south side, was likely influenced by sunlight through the windows.

For operative temperature (OT_{Ave}), it is considered that the higher impact of room temperature compared with radiant temperature is significant. For A3, the frequent use of air conditioning, as documented in Table 5, suggests that the variability in operative temperature (OT_{Ave}) may be influenced by the air conditioning temperature settings and timer settings.

SHR was significantly higher in 2023 for A1 and, although not significant, A2 showed a trend toward higher rates in 2023. It is well established that heart rate increases with temperature in summer [20]. This can be explained as follows: below 30 [°C], in a resting state, humans experience increased circulating blood volume through vasodilation of skin blood vessels, which in turn increases skin temperature, promoting heat loss from the body surface and thus regulating body temperature. Exposure to high temperatures causes an increase in heart rate as an adaptation to the decrease in blood pressure caused by vasodilation of skin blood vessels and an increase in body temperature [20]. This response can be attributed to the perception of temperature through warm sensation [24]. The higher SHR observed in 2023 for A1 and A2 can be attributed to the operative and daytime outdoor temperatures being significantly higher that year. Conversely, for A3, SHR in 2023 was significantly lower, and the daytime outdoor temperatures exhibited the opposite trend. As A3 used air conditioning, there was no significant difference in the operative temperatures between 2022 and 2023, with 2022 tending to be lower. From this, it can be inferred that SHR is unlikely to be influenced by daytime outdoor temperatures and is more likely to be affected by immediate temperatures, which aligns with findings from previous reports [23].

3.2 Impact of Bedroom Environment on SHR

Table 7 presents the Spearman's rank correlation coefficients between SHR and various environmental factors. No significant correlation was found between sleep duration and SHR.

A significant positive correlation between BM and SHR was confirmed for participants A1 and A3 when the data from 2022 and 2023 were combined. A significant positive correlation was observed for participant A2 in 2023. It is evident that body movement increases heart rate, therefore, the lack of a significant correlation for A2 may have been influenced by the inability to consider the intensity of body movement in this measurement. In a separate analysis, the investigation of other environmental factors in relation to BM revealed no significant correlations.

For daytime outdoor temperature (To), a significant positive correlation was confirmed for participants A1 and A2 when the data from 2022 and 2023 were combined. None of the participants used air conditioning during sleep, suggesting that the indoor temperature was influenced by the outdoor temperature. In contrast, no correlation was found for participant A3 in 2023, who frequently used air conditioning. This suggests that SHR was more affected by immediate temperature conditions.

A significant positive correlation was found between the average room temperature (Ta_{Ave}), radiant temperature (Tr_{Ave}), and operative temperature (OT_{Ave}) when the data from 2022 and 2023 were combined. Nakayama et al. [20] stated that heart rate increases in hot environments below 30 [°C]. As shown in Figure 3, a similar measurement range was observed in this study, thus resulting in similar findings. Within this range, an increase in temperature was associated with an increase in SHR.

For the bed microclimate temperature (Tb_{Ave}), a significant positive correlation was confirmed for participants A1 and A3 when the data from 2022 and 2023 were combined, as well as for participant A2 in 2023. According to Table 6, A1 and A2 did not use bed duvets for many days in 2023. However, A3 used a bed duvet almost every day. Assuming no body movement, constant same bed duvet use, and the participant's consistent body temperature, it was expected that the day-to-day variation in Tb_{Ave} would depend on the day-to-day variation in Ta_{Ave}. However, the influence of body heat was significant, and the day-to-day variation in Tb_{Ave} was lower than that in Ta_{Ave}. The significant correlation for A3 is likely due to the influence of indoor air temperature inhaled near the face and through breathing, in addition to the direct effect of the bed microclimate temperature on the body surface.

No significant correlation was found for carbon dioxide concentration ($CO_{2\ Ave}$), with correlations when the data from 2022 and 2023 were combined being notably lower than those observed in either year for A2 and A3. Although A3 consistently exceeded 1000 [ppm], no correlation with the SHR_{Ave} was observed.

No significant correlation was found between relative humidity (Hc_{Ave}) and SHR. In particular, for A2 and A3, the correlation was lower when the data from 2022 and 2023 were combined than over any single year, suggesting that the measured range of relative humidity did not significantly affect the SHR. Humans perceive temperature through warm receptors, and these responses are considered to influence SHR. Unlike temperature, which humans perceive through dedicated sensory organs, there are no such dedicated sensory organs for humidity, even though humans can perceive it. Therefore, it is speculated that there may be a threshold for influencing the heart rate, but the range of relative humidity measured did not lead to significant responses.

A positive correlation for illuminance (Lx_{Ave}) was observed for A2. Figure 3 indicates that the illuminance for A2 was not exceptionally high compared with that for A1. Light on the eyelids affects ipRGCs in the retina, which detects brightness [26], and prolonged stimulation of these cells is said to affect the body clock [27]. The potential influence of light on SHR was considered, though it was not clearly confirmed.

From the above, it can be inferred that in the hot environment measured in this study, the room temperature and radiant temperature had the strongest linear relationship with SHR, followed by the bed microclimate temperature. Body movements are also considered to affect SHR.

3.3 Statistical Power and Adequate Sample Size for Correlation with SHR

This section focuses on BM, OT_{Ave}, and Tb_{Ave}, which showed significant positive correlations with SHR in at least two participants when the data from 2022 and 2023 were combined. Table 8 shows the correlation coefficients and the calculated statistical power derived from the sample sizes (N), with the significance level set at 0.05. Table 9 presents the weighted correlation coefficients and p-values obtained through the meta-analysis for the three participants, with the statistical power calculated at a significance level of 0.05. The OT_{Ave} had a high statistical power for each participant, with the statistical power of meta-analytic weighted correlation coefficients exceeding 80%.

As OT_{Ave} demonstrated the highest statistical power among these three variables, the appropriate sample size required to confirm correlations with OT_{Ave} was evaluated. Using data from SHR and OT_{Ave} for the three participants, 100 sets of 10,000 bootstrap replications were conducted for each participant. This method provides robust estimates by repeatedly resampling the data to assess the stability and reliability of the correlation coefficients. Starting with 20 samples and increasing in increments of five, the average correlation coefficients and statistical power for each sample size were meta-analyzed. The results, including the 95% confidence intervals for these metrics, are shown in Figures 4 and 5.

At a sample size of 20, the statistical power approached the levels presented in Table 9, indicating a high probability of a significant correlation between SHR and OT_{Ave}. Although the average weighted correlation coefficient was equivalent to the value shown in Table 9 and the 95% confidence interval also indicated a positive correlation, the range of the weighted correlation coefficients was relatively broad at a sample size of 20. Consequently, the analysis was expanded to include two additional participants with more than 20 nights of data from the summer of 2022 (Note 4). The results are presented in Figs. 6 and 7.

This extended analysis demonstrated that the statistical power was less than 60% at a sample size of 20 but exceeded 80% when the sample size was increased to more than 35. This result likely stems from the inclusion of a participant whose positive correlation was not significant. However, with 35 samples, the likelihood of achieving significance was greater than 80%. Thus, conducting experiments for at least 35 nights or more can yield a significant positive correlation between SHR and OT_{Ave} with an 80% probability.

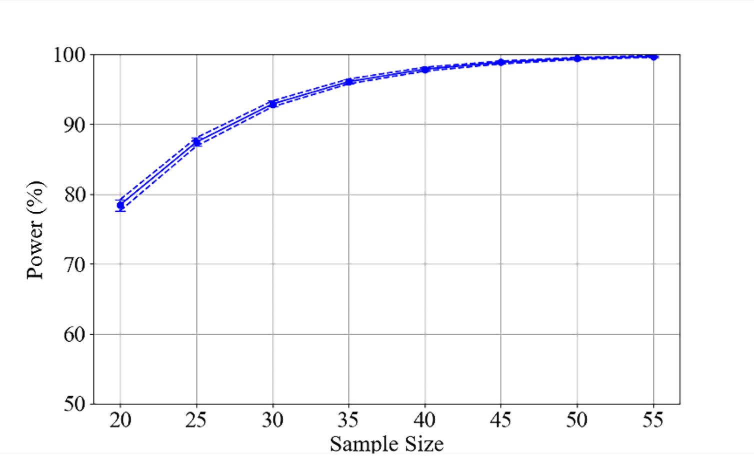


Figure 4: Power Estimates for Each Sample Size Determined by Bootstrap, with Dashed Lines Indicating the 95% Confidence Interval

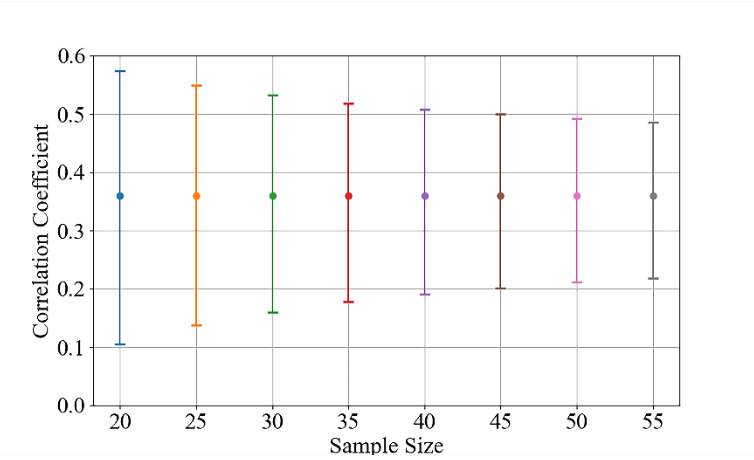


Figure 5: Bootstrap Analysis of the 95% Confidence Interval for Weighted Correlation Coefficients at Each Sample Size

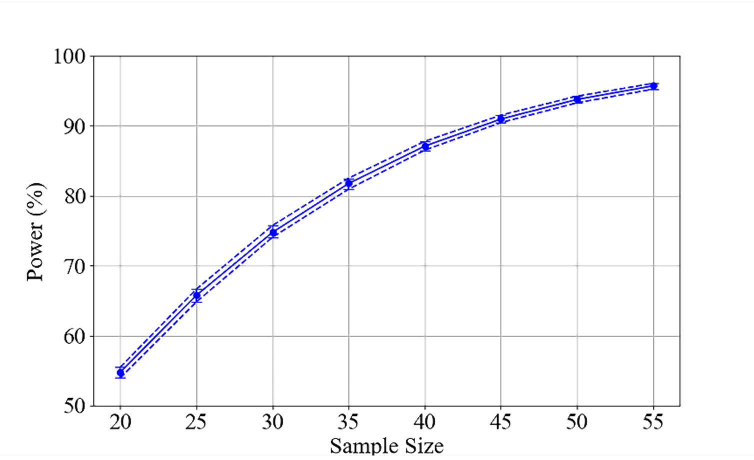


Figure 6: Bootstrap Analysis of Power for Data from Five Participants with More than 20 Nights, with Dashed Lines Indicating the 95% Confidence Interval

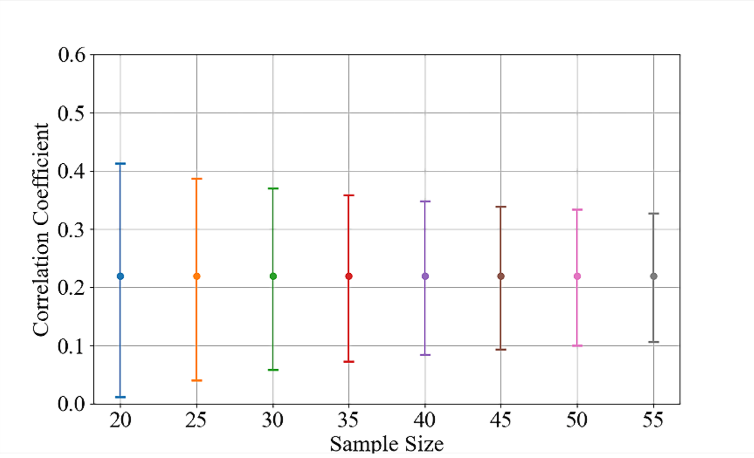


Figure 7: Bootstrap Analysis of the 95% Confidence Interval for Weighted Correlation Coefficients at Each Sample Size

3.4 Examination of Mediating Variables for SHR

Regarding the variability in Tb_{Ave}, operative temperature influences might also be present in addition to the participant's body temperature. Therefore, we explored the possibility that SHR is not only directly impacted from OT_{Ave} but also mediated through Tb_{Ave}. Table 10 presents the results of the mediator analysis examining the effect of OT_{Ave} on SHR via Tb_{Ave}. In this model, OT_{Ave} and Tb_{Ave} were used as the exposure and mediating variables, respectively, in a least squares linear regression model. Bootstrap methods with 10,000 resamples were employed for parameter estimation. ACME was not significant for any participant, and no mediating effect of OT_{Ave} on Tb_{Ave} was confirmed. Therefore, OT_{Ave} and Tb_{Ave} were independent in subsequent analyses.

Regarding the variability in BM, the impact of temperature might also be present. Therefore, the possibility SHR is not only directly impacted by OT_{Ave} or Tb_{Ave} but also mediated through BM was explored. Tables 11 and 12 present the results of the mediator analysis. The analytical method was the same as that described previously. ACME was not significant for any participant, and no mediating effects were observed.

3.5 Examination of Confounding Factors between SHR and BM

OT_{Ave} and Tb_{Ave} might influence both BM and SHR, potentially acting as confounding factors. Tables 13 and 14 present the results of the regression performed using least squares for each participant, comparing the effects adjusted for BM and the direct effects for OT_{Ave} and Tb_{Ave}, respectively.

For OT_{Ave}, the adjusted effects for BM were lower than the direct effects for all participants and significant for A1 and A2. For A2, the impact of BM was not substantial, and no consistent results were obtained across all participants, suggesting the potential, but not definitive, role of OT_{Ave} as a confounding factor.

For Tb_{Ave}, no significant effect was observed for A2. For A1 and A3, the effects adjusted for BM were lower than the direct effects, and significance was confirmed for BM. Again, no consistent results were obtained across all participants, indicating the potential, but not definitive, role of Tb_{Ave} as a confounding factor.

3.6 Examination of Optimal Models Through Multilevel Structural Analysis

Intraclass correlations were calculated for the similarity of each environmental factor in each participant's bedroom. All environmental factors, except Tb_{SD}, showed significant intraclass correlation coefficients (Note 5) with $P < 0.01$, exceeding 0.1, and the design effects (Note 5) were greater than two, confirming that these factors could be treated as multilevel data structures. The average values of each environmental factor for all measurement periods per participant were treated as 'between' levels, and the deviations from these averages on each measurement day were treated as 'within' levels. Additionally, the personal attributes from Table 1 were included 'between' levels in the multilevel structural analysis. While SHR was the dependent variable, BM, Ta_{SD}, Tr_{Ave}, Tb_{Ave}, Tb_{SD}, To, OT_{Ave}, Hc_{Ave}, Hc_{SD}, $CO_2\ _{Ave}$, $CO_2\ _{SD}$, Lx_{Ave}, and participant attributes (heat sensitivity as 1, cold sensitivity as -1, neutral as 0) were used as explanatory variables to examine the model with the highest explanatory power, judged by the magnitude of the posterior predictive p-values. Assuming a nonparametric distribution of the data obtained from the experiments, calculations were performed using Bayesian estimation with the MCMC method, employing Mplus Version 8.4 with eight Markov chains and 40,000 MCMC simulation iterations.

Table 15 shows the coefficients of each explanatory variable with the p-values and the model's DIC in the converged model with large posterior predictive p-values. In most of the models examined, the posterior predictive p-values were 0, and the models with 0 results are not displayed. Coefficients 'within' a level represented the impact of within-participant differences, and those 'between' levels represented between-participant differences.

Although various environmental factors were examined, incorporating explanatory variables other than BM, Tb_{Ave}, and OT_{Ave} into the model resulted in either non-convergence or a decrease in explanatory power. The results from Models 2, 4, 5, 7, and 8 in Table 15 show that coefficients 'between' levels were not significant, likely owing to the difficulty of verifying 'between' level effects with only three participants. In the 'within' a level analysis, the model that included only Tb_{Ave} as an explanatory variable for SHR failed to converge. Therefore, the BM and OT_{Ave} were considered appropriate variables for inclusion in the model.

As discussed in Section 4, OT_{Ave} might be considered a potential confounding factor because of its impact on both SHR and BM. Therefore, Models 6 and 9 were compared. Model 9 examined the effect of OT_{Ave} on BM, but the results did not show significant coefficients. No confounding effects of OT_{Ave} were observed.

Based on these findings, Model 6 was considered the most suitable model. Table 16 presents the standardized coefficients for this model, suggesting that OT_{Ave} had the most substantial impact on heart rate. In this model, the coefficient of determination was 0.191, indicating that both BM and OT_{Ave} accounted for approximately 19% of the total variation in SHR. In table 15 the coefficients of determination for Models 1 and 3 were 0.118 and 0.061, respectively. This shows that the explanatory powers of OT_{Ave} and BM on the total variation in SHR were approximately 12% and 6%, respectively. This result further confirms the significant impact of OT_{Ave} on SHR.

Among the environmental factors, operative temperature had the most significant impact on SHR. In summer, it is considered effective to reduce the day-to-day variation in operative temperature and consistently maintain a lower operative temperature by enhancing the thermal insulation of bedrooms, thereby improving their thermal retention, not just by relying on air conditioning, to maintain a lower SHR effectively.

4. Limitations of the Study

The results of this study pertain to healthy males in their twenties with average BMIs living in a temperate region. Based on the authors' reports [23], the impact of OT_{Ave} on SHR is significant for this demographic but cannot be generalized beyond these characteristics. Furthermore, this report was limited to typical bedroom conditions during summer and did not address extreme heat conditions or other seasons. These results are based solely on field surveys, and it is essential to verify whether similar results can be obtained in intervention studies.

5. Conclusion

This study examined the environmental factors affecting SHR during summer through experiments conducted with participants in their usual bedroom environments. The key findings are summarized as follows:

1. When evaluating SHR, the variables with the highest explanatory power were body movement and average operative temperature at night, with operative temperature having the most substantial impact.
2. The variation in SHR was approximately 0.5 [beat/min] for every 1 [°C] change in operative temperature. No mediating effects of operative temperature on bed microclimate temperature or body movement were confirmed. In addition, no confounding effects of operative temperature on body movement or SHR were identified.
3. Analysis based on the experimental results revealed that the impact of operative temperature on SHR shows a significant correlation with approximately 80% probability when data from about 35 nights was obtained.
4. No significant correlations were found between SHR and relative humidity, carbon dioxide concentration, or illuminance in the measured bedroom environment within the measured range.

Similar analyses should be conducted during other seasons to explore the factors influencing SHR variability throughout the year. This will help clarify seasonal variations and determine the optimal thermal environment. Understanding how environmental conditions affect sleep heart rate could enable the design of environments that promote a stable heart rate during sleep.

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, as the bedroom shapes and window proportions varied for each participant, the convective heat transfer coefficient (α_a) and the radiative heat transfer coefficient (α_r) were defined as follows:

$\alpha_a = \alpha_r$

The calculation formula for OT_{Ave} is shown below:

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

When the wind speed was less than 0.2 [m/s]: $OT_{Ave} = (Ta_{Ave} + Tr_{Ave}) / 2$

To: Daytime outdoor temperature [°C]

Footnotes

6 The participant experiments were conducted in accordance with 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.

7 A preliminary survey conducted in A1's home 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.

8 In the pre-sleep questionnaire, to identify psychological/social, physical, and chemical stress factors as well as daily activities that might affect physiological measurements, the following items were inquired about:

Physical stress factors: daytime outdoor heat/cold, heat/cold during work or study, daytime noise levels, subjective daytime barometric pressure changes, and humidity perception.

Physiological stress factors: the 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: 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 type of bedding.

In the wake-up questionnaire, the following items were inquired about: sleep and wake times, presence of pre-sleep exercise, wake-up method, clothing, bedding, use of cooling devices, activities during awakening, and any issues during sleep.

14 Overview of participants who participated in a similar experiment conducted in Higashi-Osaka City during the summer of 2022. The measurements were taken only in 2022, and although the residence location was different, it was in a temperate region. The participants were men in their twenties with average BMI.

Participant ID	Sex	Age	BMI	Heat Sensitivity	Daytime Location And Bedroom Location	Measurement Period	Number of Data Points
A4	Male	21	20.2	Heat Sensitivity	Higashi Osaka City	July 2 – July 27, 2022	26
A5		21	19.0	Heat Sensitivity		July 28 – Aug 31, 2022	22

16 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:

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

This is an indicator for evaluating within-group similarity; if similarity is confirmed, the data should be treated hierarchically.

MS_B: Mean Square ’between’ groups

= Sum of Squares ’between’ groups/degrees of freedom for a factor

MS_W: Mean Square ‘within’ a group

= Sum of Squares ‘within’ groups / Degrees of freedom for error

k’: Average number of data points ‘within’ a group

The design effect (DE) is calculated using the following formula:

$DE = 1 + (K' - 1) ICC$

Similarity is determined in any of the following cases:
1. ICC is significant
2. ICC exceeds 0.1
3. DE is 2 or more

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Table 1: Participant Attributes and Measurement Periods

Participant ID	Sex	Age	BMI	Heat Sensitivity	Daytime Location And Bedroom Location	Measurement Period	Number of Data Points
A1	Male	21	17.5	Neutral Thermal Sensitivity	Yonezawa City	July 5 - Aug 3, 2022	24
						Aug 10 - Sop 6, 2023	16
A2		22	21.0	Mild Heat Sensitivity		Aug 5 -Aug 29, 2022	24
						Aug 9 -Sep 3, 2023	22
A3		21	19.4	Mild Cold Sensitivity		Aug 30 - Sep 22, 2022	24
						Sep 9 -Sep 30, 2023	21

Table 2: Measured Parameters

Physiological Measures	Body Movement, Heart Rate, Respiratory Rate	
Environmental Factors	①	CO_2 concentration around the head area [ppm]
	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

CLO value: A measure of clothing insulation.

	A1		A2		A3	
	2022	2023	2022	2023	2022	2023
CLO Value	0.46±0	0.46±0	0.44±0	0.44±0	0.44±0	0.44±0

Table 4: Average Bedtime and Total Sleep Time

Values in parentheses represent the standard deviation in minutes.

	A1		A2		A3	
	2022	2023	2022	2023	2022	2023
Bedtime (hh:mm)	3:59(103)	3:35(71)	0:42(77)	0:04(102)	0:53(48)	0:22(47)
Total Sleep Time (hh:mm)	5:44(82)	5:54(45)	6:51(53)	7:00(91)	7:24(17)	7:48(45)

Table 5: Number of Days Using Air Conditioning, Fans, and Open Windows

	A1		A2		A3	
	2022	2023	2022	2023	2022	2023
Air Conditioning	0	0	0	0	8	13
Fan	0	0	0	0	0	0
Open Windows	0	0	0	22	0	0

Table 6: Usage of Bed Duvet

	A1		A2		A3	
	2022	2023	2022	2023	2022	2023
Towel Blanket	8	0	0	5	23	0
Duvet	5	3	24	10	1	21

Table 7: Spearman's Rank Correlation Coefficients Between SHR_{Ave} and Environmental Factors

**: $P < 0.01$ *: $P < 0.05$, N: sample size

		Duration	BM	To	Ta_{Ave}	Tr_{Ave}	OT_{Ave}	Tb_{Ave}	$CO_{2\ Ave}$	Hc_{Ave}	Lx_{Ave}
A1	2022	0.08	0.60**	0.16	0.23	0.19	0.21	0.15	0.80	0.04	0.15
	N	23	23	23	23	23	23	23	5	23	23
	2023	0.42	0.30	0.17	0.15	0.11	0.11	0.00	0.27	0.36	0.01
	N	16	16	16	16	16	16	16	16	16	16
	22&23	0.04	0.56**	0.35*	0.40*	0.35*	0.33*	0.35*	0.37	0.08	0.14
	N	39	39	39	39	39	39	39	21	39	39
A2	2022	0.12	0.20	0.50*	0.49*	0.50*	0.47*	0.11	0.21	0.22	0.49*
	N	24	24	24	24	24	24	24	24	24	24
	2023	0.38	0.52*	0.11	0.11	0.14	0.14	0.55**	0.07	0.03	0.43*
	N	22	22	22	22	21	21	22	22	22	22
	22&23	0.23	0.09	0.33*	0.31*	0.34*	0.34*	0.24	0.07	0.03	0.34*
	N	46	46	46	46	45	45	46	46	46	46
A3	2022	0.04	0.44*	0.42*	0.59**	0.58**	0.58**	0.30	0.13	0.10	0.01
	N	24	24	23	24	24	24	24	24	24	24
	2023	0.31	0.63**	0.01	0.13	0.13	0.13	0.34	0.21	0.06	0.20
	N	21	21	21	21	21	21	21	15	21	21
	22&23	0.02	0.50**	0.19	0.32*	0.31*	0.41**	0.34*	0.03	0.06	0.04
	N	45	45	44	45	45	45	45	39	45	45

Table 8: Power Analysis of the Correlation Tests Between SHR and Various Variables

r: correlation coefficient, ** $P < 0.01$, * $P < 0.05$, N: sample size.

		BM	OT_{Ave}	Tb_{Ave}
A1	r	0.56**	0.33*	0.35*
	N	39	39	39
	Statistical Power	0.99	0.69	0.74
A2	r	0.09	0.34*	0.24
	N	46	45	46
	Statistical Power	0.15	0.77	0.50
A3	r	0.50**	0.41**	0.34*
	N	45	45	45
	Statistical Power	0.98	0.91	0.77

Table 9: Meta-Analysis of Weighted Correlation Coefficients for SHR Across Three Participants

	BM	OT_{Ave}	Tb_{Ave}
Weighted Correlation Coefficient	0.33	0.36	0.30
95%CI	0.16 - 0.48	0.20 - 0.51	0.14 - 0.46
P Value	< 0.001	< 0.001	< 0.001
Statistical Power	0.76	0.82	0.69

Table 10: Mediating Effects of OT_{Ave} to Tb_{Ave} on SHR

ACME: Average Causal Mediation Effect; ADE: Average Direct Effect.

		Estimate Value	P-value
A1	ACME	0.210	0.257
	ADE	0.504	0.027
	Total Effect	0.714	0.007
A2	ACME	0.007	0.947
	ADE	0.510	0.039
	Total Effect	0.517	0.059
A3	ACME	0.168	0.167
	ADE	0.217	0.350

Total Effect	0.385	0.100

Table 11: Mediating Effects of OT_{Ave} to BM on SHR

ACME: Average Causal Mediation Effect; ADE: Average Direct Effect.

		Estimate Value	P-value
A1	ACME	0.106	0.747
	ADE	0.594	0.001
	Total Effect	0.700	0.100
A2	ACME	0.014	0.893
	ADE	0.510	0.048
	Total Effect	0.524	0.049
A3	ACME	0.137	0.504
	ADE	0.251	0.185
	Total Effect	0.388	0.163

Table 12: Mediating Effects of Tb_{Ave} to BM on SHR

ACME: Average Causal Mediation Effect; ADE: Average Direct Effect.

		Estimate Value	P-value
A1	ACME	0.271	0.473
	ADE	0.820	0.041
	Total Effect	1.091	0.060
A2	ACME	-0.009	0.935
	ADE	0.518	0.190
	Total Effect	0.509	0.209
A3	ACME	0.624	0.067
	ADE	0.856	0.136
	Total Effect	1.480	0.021

Table 13: Direct Effects of OTAve on SHR and Adjusted Effects for BM

		Estimate Value	P-value
A1	OT_{Ave}	0.600	0.017
	BM	26.980	0.000
	OT_{Ave}	0.711	0.017
A2	$OT_{,Ave}$	0.524	0.035
	BM	-1.693	0.718
	OT_{Ave}	0.536	0.028
A3	OT_{Ave}	0.248	0.161
	BM	27.990	0.002
	OT_{Ave}	0.380	0.050

Table 14: Direct Effects of Tb Ave on SHR and Adjusted Effects for BM

		Estimate Value	P-value
A1	Tb_{Ave}	0.845	0.053
	BM	26.631	0.000
	Tb_{Ave}	1.108	0.029
A2	Tb_{Ave}	0.524	0.219
	BM	-3.187	0.509
	Tb_{Ave}	0.516	0.223
A3	Tb_{Ave}	0.816	0.176
	BM	26.687	0.003
	Tb_{Ave}	1.431	0.024

Table 15: Results of Multilevel Structural Equation Modeling with SHR as the Dependent Variable

Model				Estimate	P-value	Posterior Predictive P-value	DIC
No.	Level	Dependent Variable	Explanatory Variable				
1	Within	SHR	OT	0.543	0	0.004	574.793
			Residual	4.915	0		
2	Within	SHR	OT	0.536	0	0.100	1050.492
			Residual	4.949	0		
	Between		OT	2.076	0.319		
3	Within	SHR	BM	9.806	0.005	0.002	588.345
			Residual	5.269	0		
4	Within	SHR	BM	9.736	0.005	0.043	206.977
			Residual	5.274	0		
	Between		BM	203.651	0.247		
5	Within	SHR	Tb	0.918	0	0.103	888.241
			Residual	5.074	0		
	Between		Tb	1.690	0.324		
6	Within	SHR	BM	9.413	0.004	0.470	568.753
			OT	0.545	0		
			Residual	4.698	0		
7	Within	SHR	BM	9.521	0.005	0.485	1045.133
			OT	0.529	0		
			Residual	4.710	0		
	Between		OT	1.983	0.318		
8	Within	SHR	BM	9.472	0.004	0.555	663.739
			OT	0.529	0		
			Residual	4.708	0		
	Between		OT	2.281	0.496		
			BM	1.017	0.494		
9	Within	SHR	BM	9.394	0.004	0.491	213.836
			OT	0.537	0		
			Residual	4.684	0		
		BM	OT	0.004	0.126		
			Residual	0.004	0		

Table 16: Standardized Coefficients for Model 6

	Estimate Value	P-value
BM	0.234	0.004
OT_{Ave}	0.336	0.000
Residual	0.809	0.000