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Effects of crown closure changes in broad-leaved forests on thermal comfort and human responses according to season

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The aim of this study is to investigate the effects of crown closure seasonal changes in broad-leaved forests on the thermal comfort and the human responses. The participants were a total of 146 male and female university students. The participants sat in a chair and rested in forests with a high and low crown closure, and then closed their eyes and rested for 5 min. The thermal comfort (predicted mean vote, predicted percentage of dissatisfaction) and the physiological (forehead temperature, blood pressure, pulse rate, heart rate variability, heart rate) and psychological (thermal sensation vote, comfort sensation vote) responses were measured. The comparisons of thermal comfort and the physiological and psychological responses in forests with high and low crown closure were performed in each season. As a result, forests with high crown closure had higher thermal comfort than forests with low crown closure in summer, fall, and winter, and results related to physiological and psychological responses were more relaxed in all seasons. In conclusion, this study found that forests with high crown closure is more effective to enhance thermal comfort and relax human responses according to season.

Keywords Canopy shade, Physical environmental factors, Physiological relaxation, Seasonal differences, Thermal sensation, Tree density

Recent reductions in green space and increased building density have led to various issues in cities, such as increased energy consumption due to the urban heat island effect[1] and elevated heat stress[2]. Among these issues, heat stress has been shown to affect mortality rates[3] and is particularly lethal to the elderly and children[4], highlighting the urgent need to develop measures to address this issue. To alleviate this problem, the construction of urban green spaces has emerged as a viable solution[5].

Urban green space is considered an essential component of cities because it provides cooling effects through the shading and evapotranspiration of vegetation[6–9]. Lawns and water bodies are also important structural components of urban green spaces, but among them, trees are the most significant contributors to the cooling effect[10,11]. Unlike other elements, trees can directly control the amount of solar radiation through their crowns, thereby significantly influencing thermal comfort in urban environments[12,13]. This can also affect the physiological responses of humans[14]. Consequently, extensive research has been conducted on planting trees in urban green spaces to mitigate heat stress and enhance thermal comfort[15–20].

Numerous studies have investigated the most suitable tree species that can be planted to maximize thermal comfort in urban green spaces. Most of these studies indicated that planting broad-leaved trees with dense crowns was most appropriate, as they effectively block solar radiation. Rahman et al. found that *Tilia cordata* was more effective at enhancing thermal comfort than *Robinia pseudoacacia* in Germany, as it has a relatively higher degree of solar radiation blocking[15]. Furthermore, De Abreu-Harbich et al. compared 12 tree species aimed at enhancing thermal comfort in Brazil, with *Caesalpinia pluviosa*, which has a high solar radiation attenuation rate, being evaluated as the most ideal[16]. Sayad et al. reported that *Ficus nitida* is suitable for increasing thermal comfort during summer in Algeria, attributing this to its rounded and dense canopy, which blocks solar radiation[17].

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Additionally, there have been many studies on the planting patterns of trees, and it is generally considered ideal to plant trees densely to create sufficient shade. Chen et al. reported that densely planted trees along streets in China can effectively enhance pedestrian thermal comfort compared to less densely planted trees[18]. Srivanit & Hokao suggested that increasing the number of planted trees by 20% could lower the average temperature of outdoor spaces in Japan during summer by up to 2.27 °C, thereby improving outdoor thermal comfort[19]. Zölch et al. revealed that maximizing the number of trees within urban green spaces in Germany to increase shade is the most effective approach for enhancing thermal comfort[20].

However, some broadleaf trees shed their leaves seasonally, leading to changes in crown closure, potentially altering thermal comfort. Crown closure is a measure of the ground area covered by the tree canopy in a stand[21]. In cold weather, areas with high crown closures may block solar radiation, leading to thermal discomfort[22]. Furthermore, when leaves are shed, the crown closure decreases, and even densely planted trees may not necessarily improve thermal comfort. To mitigate thermal stress within urban green spaces by planting deciduous trees, it is necessary to systematically consider how thermal comfort varies with changes in canopy density throughout the year. Despite this need, most studies on thermal comfort in urban green areas and forests have primarily focused on alleviating thermal stress during summer or in hot climates[23–26]. For instance, Liu et al. indicated that air temperature and solar radiation are key determinants of outdoor thermal comfort based on a study conducted in hot-summer and cold-winter climates[27]. However, research on thermal comfort during non-warm seasons remains significantly limited.

Therefore, this study aimed to measure the physical environmental factors, thermal comfort, human physiological responses, and subjective thermal comfort at experimental sites where canopy density varies seasonally. How these factors changed compared to the control sites with relatively stable crown closures was also analyzed.

Methods

Participants

This study was approved by the Institutional Review Board of the Kongju National University (KNU_IRB_2022 – 108) and all methods were performed in accordance with the relevant guidelines and regulations of the Declaration of Helsinki. The study participants were healthy adults aged 18 years or older. Those who were unable to communicate and individuals with illnesses, hypertension, and a history of heart or cerebrovascular disease were excluded. The sample size for this study was determined using the program G-power 3.1. The analysis method employed was t-tests; Means: Difference between two dependent means (matched pairs), with an effect size of 0.7, a significance level (α err prob) of 0.05, and a power (1-β err prob) of 0.95. The appropriate sample size for the present study was determined to be 24 participants. This study was conducted in an outdoor forest environment and dropouts were expected to occur. Therefore, a dropout rate of 20% (five individuals) was set. Considering both the appropriate sample size and dropout rate, 29 participants were required for this study. Finally, 146 participants (spring: 40; summer: 31; fall: 39; winter: 36) participated in this study. Detailed experimental data and participant characteristics are presented in Table 1.

Experimental site

This study was conducted in the Kongju National University forest with approval of the forest director. To investigate the effect of seasonal changes in canopy closure on thermal comfort and human responses, experimental sites (36°40′00.90″N, 126°51′58.22″E) and control sites (36°39′58.92″N, 126°51′58.66″E) were selected. The crown closure of the sites was determined using photographs taken with a Sigma EX DG fisheye lens (1:3.5) mounted on a Canon EOS 5D camera and analyzed by the Gap Light Analyzer program (Table 2). In this study, areas with high crown closure during the summer were designated as experimental sites, while those with low crown closure were selected as control sites (Table 3).

Figure 1 shows the crown projections of the experimental and control sites. Circular quadrats (radius: 11.3 m, area: 400 m^2) were established around the seating positions of the study participants for vegetation and tree surveys. The tree species that comprised the crown at the experimental site included *Quercus acutissima*,

Season	Spring	Summer	Fall	Winter
Date	’23. 04. 28 – 05. 01.	’22. 08.18 – 08. 22.	’22. 11. 04 – 11. 06.	’23. 02. 27 – 03. 01.
N	40 (male: 20, female: 20)	31 (male: 15, female: 16)	39 (male: 22, female: 17)	36 (male: 17, female: 19)
Age (years)	21.8 ± 1.9	21.5 ± 2.1	22.1 ± 2.1	21.8 ± 1.5
Height (cm)	166.2 ± 9.4	168.5 ± 11.1	168.4 ± 8.7	165.7 ± 9.4
Weight (kg)	63.7 ± 11.7	64.81 ± 1.5	65.4 ± 12.9	65.1 ± 13.6
Body mass index (km/m^2)	23.0 ± 2.9	22.5 ± 2.9	22.9 ± 3.2	23.6 ± 3.9

Table 1. Experiment date and characteristics of participants. (mean ± standard deviation).

Season site	Spring	Summer	Fall	Winter
Experimental site				
Crown closure (%)	57.7	76.6	51.1	27.3
Control site				
Crown closure (%)	18.5	25.9	21.7	5.7

Table 2. Photographs of the crown closure (%) in experimental and control sites for all seasons.

Date	Experimental site	Control site
Altitude (m)	119	126
Aspect (°)	297	330
Slope degree (°)	15	5
Litter layer (cm)	3	1

Table 3. Location characteristics of the experimental and control sites in this study.

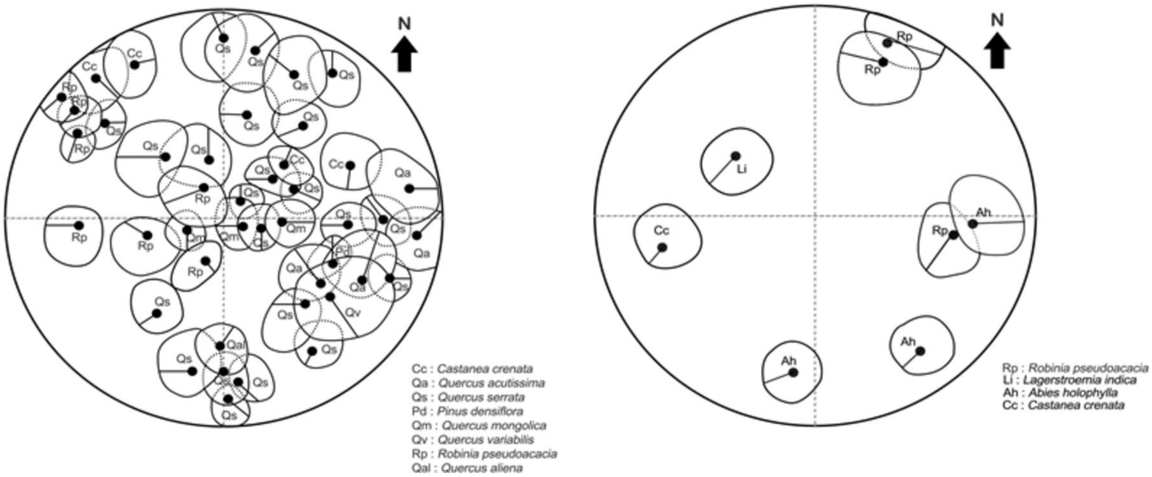

Fig. 1. Crown projection of experimental (left) and control (right) site for all seasons.

Quercus. serrata, *Quercus. variabilis*, and *Robinia. pseudoacacia*, whereas the crown at the control site consisted only of *Robinia. pseudoacacia*.

Experimental design

The overall experimental procedure and sequence are illustrated in Fig. 2. This study was conducted using a within-subject experimental design; participants were paired and moved to different locations, to exclude the influence of stimulus presentation order. After the initial measurements were taken at each location, the participants crossed over. Those initially measured at the experimental site were moved to the control site, whereas those initially measured at the control site were moved to the experimental site. The experiments were conducted simultaneously at each location using the same procedure (Fig. 2).

The detailed experimental procedure was as follows. Participants were suggested to get sufficient sleep the night before the experiment and to abstain from meals, caffeinated beverages, and nicotine intake for two hours prior to the start of the experiment. On the day of the experiment, the participants arrived at the waiting room where they received a thorough explanation of the study and completed an informed consent form. Subsequently, they were fitted with devices to measure their body temperature, heart rate variability, and heart rate. Data collection began at this point and continued until the end of the experiment. Following the instructions provided by the experimenters, the participants arrived at each research site and sat comfortably on a chair for 5 min to exclude the influence of movement on the physiological variables. As confirmed in our previous study[28] monitoring physiological responses before and after high-intensity exercise (7.38 met), indicators such as blood pressure and pulse rate stabilized after 5 min of exercise. In this study, as the participants moved on a flat terrain for approximately 2 min, we determined that a 5-minute break would be sufficient for stabilizing the physiological response. Subsequently, they rested with their eyes closed and wore earplugs to block visual and auditory stimuli for 5 min. The average forehead temperature, heart rate variability, and heart rate at that time were used for analysis. Blood pressure and heart rate were measured, and a questionnaire on subjective thermal sensation and comfort was administered.

Measurements

Physical environmental factors

To investigate the physical environmental factors, temperature, wind speed, relative humidity, and black globe temperature were measured. The mean radiant temperature (MRT), estimated using a globe thermometer, is based on the assumption that the radiant heat transfer depends on the surface temperature of the globe, while convection can be estimated using air temperature and wind speed as proxies[29]. The MRT was calculated based on the values of variables such as globe temperature, air temperature, wind speed, emissivity, and the diameter of the globe thermometer, and the calculation formula for MRT[30] is as follows:

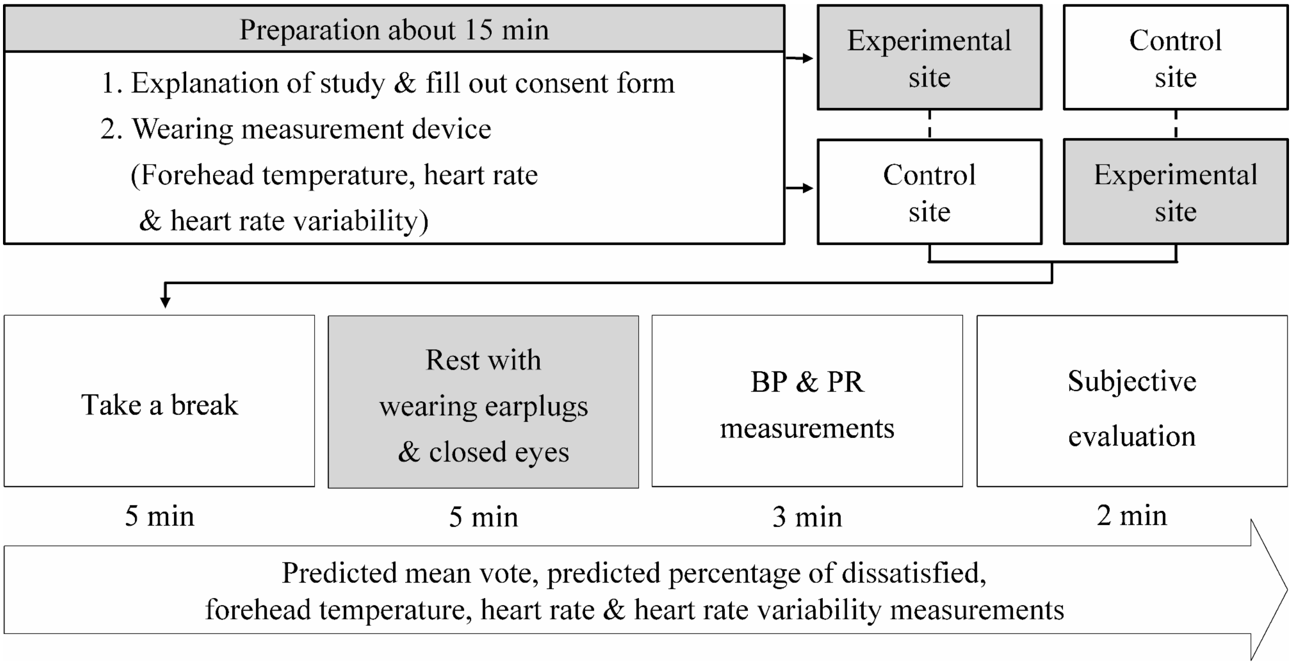

Fig. 2. Flow diagram explaining the experimental process used in this study.

$$\bar{t}_r = \left[(t_g + 273)^4 + 2.5 \times 10^8 \times v_a{}^{0.6}(t_g - t_a)\right]^{1/4} - 273$$

$\bar{t}_r$: the mean radiant temperature

t_g: the temperature of the black globe
v_a: the air velocity
t_a: the air temperature

Python (pycharm) and CBE Thermal Comfort Tool[31] were utilized during the calculation process. In this study, a portable weather environmental measurement device (Kestrel 5400, Nielsen Kellerman Corporation, USA) was used to measure at 1-min intervals from 09:00 to 18:00. Measurement was conducted only during the experiment, and the installation height of the device was standardized to 1.5 m for all seasons and locations.

Thermal comfort indicators

The predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD) were used as indices to assess thermal comfort in the thermal environment[32]. The calculation formula for PMV[33] is as follows, and the formulas for t_{cl} and h_c can be obtained through iterations:

$$PMV = [0.303 \times exp(-0.036 \times M) + 0.028] \left\{ \begin{array}{l} \times (M - W) - 3.05 \times 10^{-3} \times [5,733 - 6.99 \times (W - M) - Pa] - 0.42 \\ \times [(M - W) - 58.15] - 1.7 \times 10^{-5} \times M \times (5,867 - P_a) - 0.0014 \times M \\ \times (34 - t_a) - 3.96 \times 10^{-8} \times f_{cl} \times (t_{cl} + 273)^4 - (+273)^4] - f_{cl} \times h_c \times (t_{cl} - t_a) \end{array} \right\}$$

$$\begin{array}{l} t_{cl} = 35.7 - 0.028 \times (M - W) - I_{cl} \times \{3.96 \times 10^{-8} \times f_{cl} \\ \quad \times [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} \times h_c \times (t_{cl} - t_a)\} \end{array}$$

$$h_c = \begin{array}{ll} 2.08 \times |t_{cl} - t_a|^{0.25} & \text{for } 2.38 \times |t_{cl} - t_a|^{0.25} > 12.1 \times \sqrt{V_{ar}} \\ 12.1 \times \sqrt{V_{ar}} \times & \text{for } 2.38 \times |t_{cl} - t_a|^{0.25} < 12.1 \times \sqrt{V_{ar}} \end{array}$$

$$f_{cl} = \begin{array}{ll} 1.00 + 1.290 I_{cl} & \text{for } I_{cl} \leq 0.078\,\mathrm{m}^2 \times \mathrm{K/W} \\ 1.05 + 0.645 I_{cl} & \text{for } I_{cl} > 0.078\,\mathrm{m}^2 \times \mathrm{K/W} \end{array}$$

$$\mathrm{PPD} = 100 - 95 \times \exp\left(0.03353 \times \mathrm{PMV}^4 - 0.2179 \times \mathrm{PMV}^2\right)$$

Where M = metabolic free energy production per unit body area (W/m^2); W = external mechanical work per unit area (W/m^2); I_{cl} = Intrinsic clothing insulation ($m^2 \times K/W$); f_{cl} = clothing area factor; t_a = air temperature (°C); t_r = mean radiant temperature; V_{ar} = air velocity (m/s); P_a = partial pressure of water vapor in air (Pa); h_c = convective heat transfer coefficient [$W/(m^2 \times K)$], and t_{cl} = surface temperature of clothed body (°C).

The PMV is an index that predicts the average sensation of thermal comfort, representing the degree of heat or cold expressed by a large group of people on a 7-point scale[33]. PPD is the proportion of people in a large group who are thermally dissatisfied because they feel too hot or cold[33]. The PMV and PPD were calculated based on temperature, mean radiant temperature, air velocity, relative humidity, metabolic rate, and clothing insulation[33].

PMV has been extensively employed for evaluating indoor environments and is recognized by ISO 7730 and ASHRAE Standard 55. Although it was originally developed for steady-state conditions, it can also be applied to outdoor settings with minor dynamic fluctuations[33]. In addition, the need for model modifications to account for radiation components in outdoor environments remains a topic of debate[34]. Despite this, PMV continues to be a standard metric for comparing thermal comfort in both indoor and outdoor environments, including urban green areas. Therefore, this study employed PMV·PPD as indicators of thermal comfort.

In this study, the metabolic rate was set to 1.0 met, corresponding to the resting metabolic rate while seated. Clothing insulation was standardized within each season to minimize bias by suggesting to wear a specific type (Table 4).

Physiological indicators

Forehead temperature The body temperature is a physiological response that maintains homeostasis and ensures stability. In this study, the forehead temperature, which can physiologically represent outdoor thermal comfort and the influence of tree shade, was measured[35]. Forehead temperature was measured at 1-s intervals using an LT-8 A device (Technox, Korea). A forehead thermometer was attached to the forehead using adhesive medical tape.

Pulse rate and blood pressure Using an automatic blood pressure monitor (P2100 model, Terumo, Japan), the pulse rate, systolic and diastolic blood pressure were measured. The participants were seated in a chair facing forward, with their shoulders aligned horizontally, and their pulse rate and blood pressure were measured once. If errors occurred during the measurement process, a remeasurement was conducted. Due to inaccurate measurements caused by wearing thick clothing during fall and winter, participants were instructed to temporarily remove the outerwear on the arm before the measurements were taken.

Heart rate and heart rate variability The heart rate (HR) was measured using an electrocardiogram monitor (WHS-1, UNION TOOL CO., Japan) attached to the chest area to measure the number of heartbeats per minute for the duration of 1 min.

Autonomic nervous system responses were measured by heart rate variability (HRV). The interval between R waves (R–R Interval; RRI) was measured using the same electrocardiogram monitor used for the heart rate measurements[36]. Frequency analysis of RRI data was performed using the maximum entropy method (MemCalc/win; GMS, Japan), and low frequency (LF, 0.04–0.15 Hz), high frequency (HF, 0.15–0.4 Hz), and the LF/HF ratio were calculated[37]. The HF value reflects parasympathetic nervous system activity, which is activated during physiological relaxation, whereas the LF/HF ratio reflects sympathetic nervous system activity, which is activated during tension or stress[38].

Subjective thermal comfort evaluation

Thermal sensation vote and comfort sensation vote The subjective thermal sensation vote (TSV) and comfort sensation vote (CSV) were used as subjective thermal comfort evaluation indicators[39]. TSV was evaluated on a 7-point scale ranging from “hot” to “cold,” while CSV was assessed on a 4-point scale ranging from “comfortable” to “very uncomfortable.”

Statistical analysis

This study conducted an analysis by extracting and comparing the values of the physical environmental factors, thermal comfort, body temperature, HR, HRV, and subjective evaluations between the experimental and control groups across different seasons. Welch’s t-test was employed for the analysis of the physical environmental factors and thermal comfort indicators, whereas a paired t-test was used for the physiological response indicators. The Wilcoxon signed-rank test was used to analyze the subjective evaluation indicators. A statistical significance level of $p < 0.05$ was set, and two-tailed tests were conducted. SPSS 27.0 (IBM Corp., Armonk, NY, USA) was used for adherence to standard procedures in academic research and data analysis.

Season	Spring		Summer		Fall		Winter	
Top	Normal, long sleeves	0.20	Short sleeves	0.15	Normal, long sleeves	0.20	Flannel shirt, long sleeves	0.30
	Jacket	0.35	-	-	High-insulation jacket	0.4	Parka	0.70
Bottom	Normal trousers	0.25	Normal trousers	0.25	Normal trousers	0.25	Normal trousers	0.25
	Socks	0.02	Socks	0.02	Socks	0.02	Thick, long socks	0.10
Underwear	Panties	0.03	Panties	0.03	Panties	0.03	Panties	0.03
Shoes	Shoes (thick-soled)	0.04	Shoes (thin-soled)	0.02	Shoes (thick-soled)	0.04	Shoes (thick-soled)	0.04
Sum	0.89 clo		0.47 clo		0.94 clo		1.42 clo	

Table 4. Seasonal clothing and thermal insulation.

Results

Physical environmental factors

The measurement results of physical environmental factors are as follows (Fig. 3). Air temperature was significantly different between the experimental and control sites across all seasons ($p < 0.01$). The temperature at the experimental site was significantly lower in spring, summer, and winter, and significantly higher in fall.

Similarly, the MRT exhibited a significant difference between the experimental and control sites across all seasons ($p < 0.05$). The MRT at the experimental site was significantly lower in spring and summer and significantly higher in fall and winter. The deviation in MRT across seasons was smaller at the experimental site than in the control group. The lower MRT in spring and summer at the experimental site is possibly due to the lower level of radiant heat when the crown closure is high and the degree of ground radiation is low. Furthermore, the higher MRT at the experimental site compared to the control site in fall and winter could be attributed to the relatively higher crown closure and tree density at the experimental site, leading to wind obstruction.

The experimental site consistently exhibited significantly lower wind speeds than the control site across all seasons ($p < 0.05$). Relative humidity was significantly lower at the experimental site than at the control site in spring and fall, whereas it was significantly higher in summer and winter ($p < 0.05$).

Thermal comfort

The results of thermal comfort evaluation are as follows (Fig. 4). For the PMV, the experimental site was closer to 0 (neutral) than the control site during summer, fall, and winter, indicating a more thermally comfortable environment. However, in spring, the experimental site deviated significantly from the control site, indicating a more uncomfortable environment with a negative score ($p < 0.05$).

PPD, which correlated with PMV, showed similar results. In summer, fall, and winter, the dissatisfaction rate at the experimental site was significantly lower than that at the control site. However, it was significantly higher in spring ($p < 0.05$).

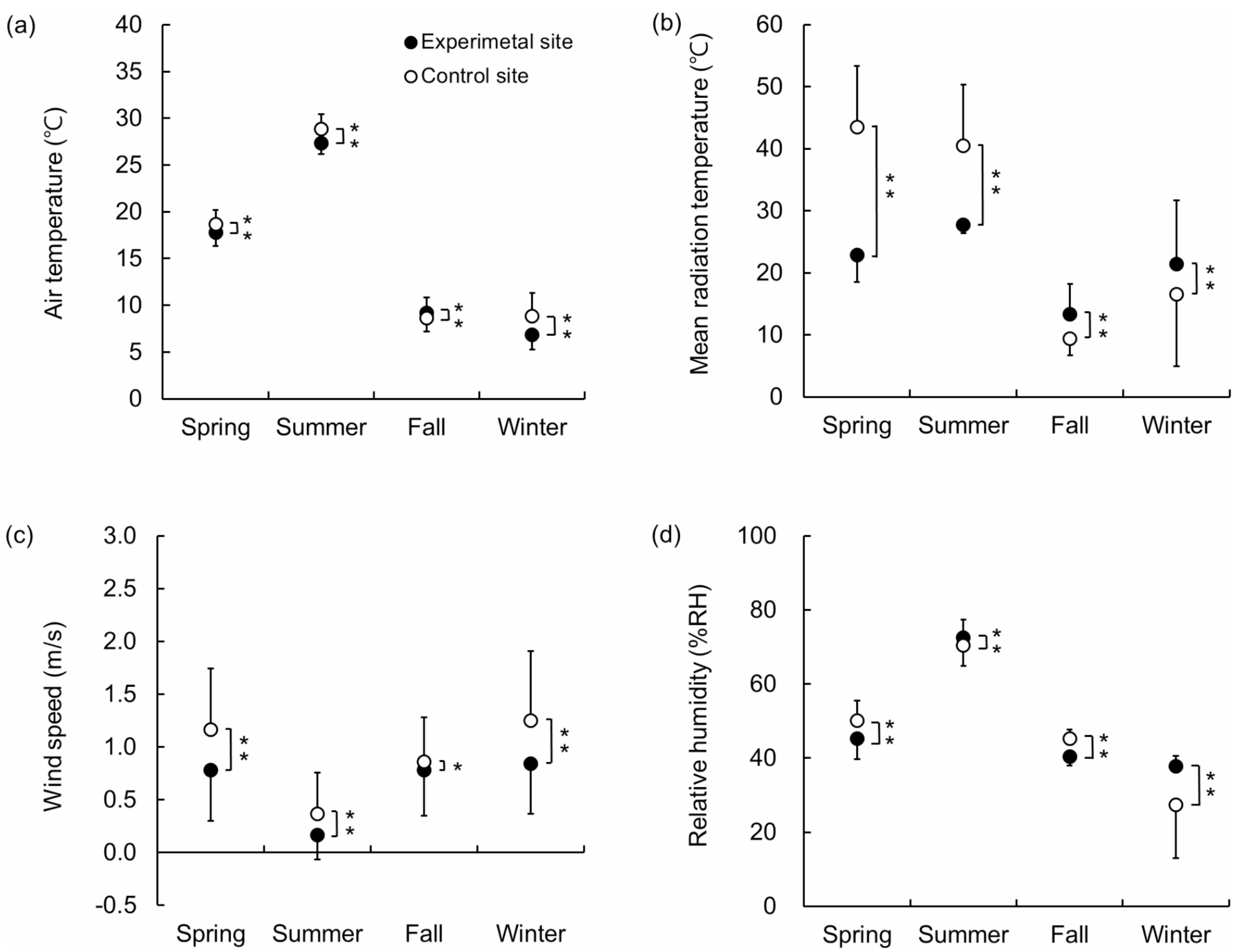

Fig. 3. Results of physical environmental factors; (**a**) air temperature, (**b**) mean radiation temperature, (**c**) wind speed, (**d**) relative humidity. $N = 1,444$ (spring: $n = 361$; summer: $n = 361$; fall: $n = 361$; winter: $n = 361$). Analyzed by Welch's t-test, mean ± standard deviation. * $p < 0.05$, ** $p < 0.01$.

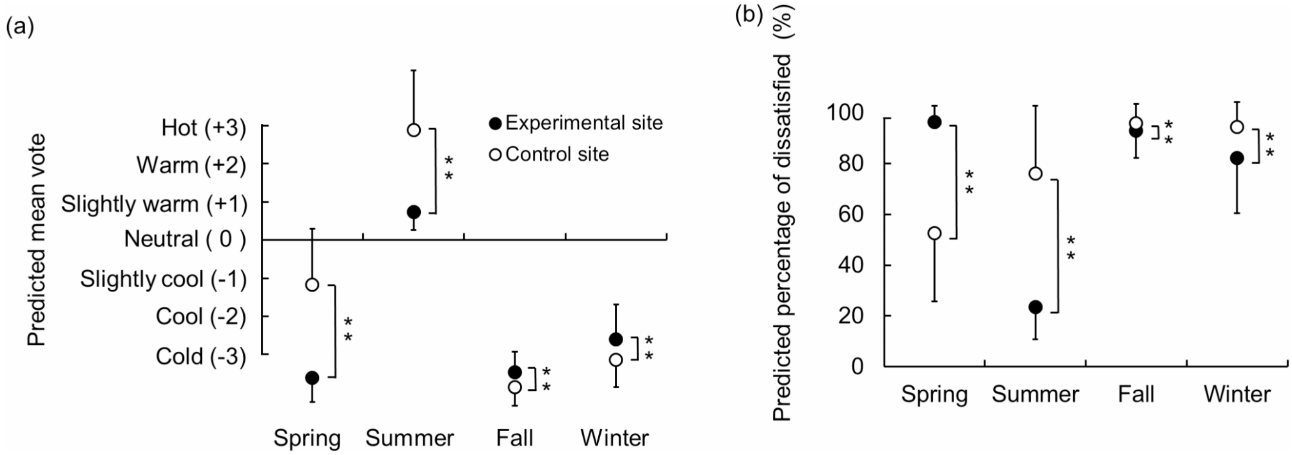

Fig. 4. Results of thermal comfort analyses: (**a**) predicted mean vote (PMV), (**b**) predicted percentage of dissatisfied participants (PPD). $N = 1,444$ (spring: $n = 361$; summer: $n = 361$; fall: $n = 361$; winter, $n = 361$). Analyzed by Welch's t-test, mean ± standard deviation. * $p < 0.05$, ** $p < 0.01$.

Physiological indicators

The results of physiological indicators are as follows (Fig. 5). Significant differences in the forehead temperature were observed across all seasons ($p < 0.05$). During spring and summer, the forehead temperature at the experimental site was lower than that at the control site, whereas during fall and winter, it was higher at the experimental site.

In the case of pulse rate, significant differences were observed during spring and summer, with the experimental site showing lower values than those of the control site ($p < 0.01$). The HR exhibited a pattern similar to that of the pulse rate.

In the case of blood pressure, significant differences were observed in some seasons ($p < 0.05$). Systolic blood pressure was lower at the experimental site than at the control site during fall, whereas diastolic blood pressure was lower at the experimental site during summer and fall. HRV showed no significant results for both HF and LF/HF.

Subjective evaluation

The subjective evaluation results are as follows (Fig. 6). The TSV revealed that, except for spring, the experimental site exhibited scores close to neutral (0) compared to the control site during summer, fall, and winter, with all differences being significant ($p < 0.05$). However, in spring, the experimental site was slightly cooler (−0.8), while the control site was slightly warmer (0.7), and this difference was significant ($p < 0.05$).

Subjective comfort sensation showed that the experimental site exhibited scores close to comfortable (0) compared with the control site across all seasons, and the difference was significant in all cases ($p < 0.05$).

Discussion

The results of the measurements of physical environmental factors, thermal comfort, physiological indicators, and subjective evaluations conducted seasonally revealed significant differences between the experimental and control sites.

In the case of spring, a significant difference was observed in the physical environmental factor of MRT, with the experimental site being approximately 20 °C lower than that at the control site. Additionally, the PMV of the experimental site was "very cold," and the PPD was predicted to be close to 100%. This is believed to be due to the significant difference in the MRT between the experimental and control sites, resulting from differences in solar radiation due to the extent of crown closure at the time of the experiment, which excessively influenced the PMV and PPD, compared with the actual conditions.

In this study, considering the relevance of previous research measuring thermal comfort in urban green spaces, the PMV and PPD were used as thermal comfort indicators. However, it has been suggested that these two indices may not be suitable for outdoor and variable environments[34]. In addition, some modifications to the model are necessary for outdoor applications[40]. In this study, the discrepancy between the thermal comfort of the spring calculated by the PMV and PPD and the subjective evaluation results suggests that the perceived thermal comfort may differ from the calculated values. One can conclude that the extremely negative predictions of PMV and PPD were attributed to colder conditions at the experimental site than those at the control site in spring. However, this is likely due to the significantly lower MRT at the experimental site compared to the control site, driven by the difference in insolation levels caused by crown closure at the time of the experiment. The algorithm used to calculate PMV places considerable weight on MRT, which may have excessively influenced the results. Consequently, the PPD values derived from PMV calculations were also affected. Therefore, for future objective evaluations of thermal comfort in urban green spaces, it is necessary to compare various indicators, including subjective measurement indicators.

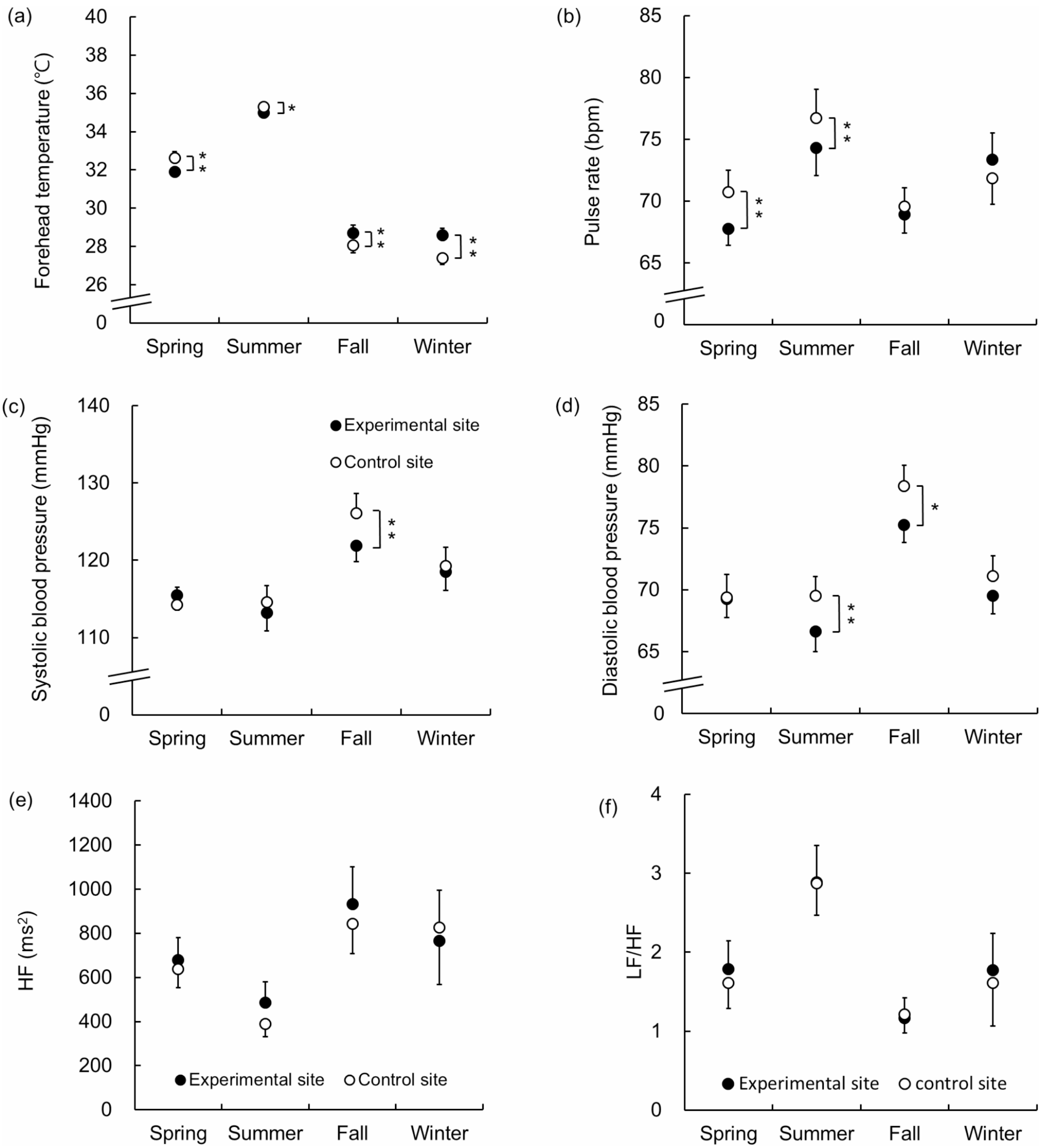

Fig. 5. Results of physiological indicators; (**a**) forehead temperature, (**b**) pulse rate, (**c**) systolic blood pressure, (**d**) diastolic blood pressure, (e) HF, (f) LF/HF. $N = 139$ (spring: $n = 38$; summer: $n = 30$; fall: $n = 36$; winter: $n = 35$). Analyzed by Welch's t-test, mean ± standard error. * $p < 0.05$, ** $p < 0.01$.

In the summer, the difference in crown closure between the experimental and control sites was the most pronounced. In particular, the experimental site exhibited the most positive thermal comfort and subjective evaluation results in summer among all the seasons, indicating physiological stability. This aligns with previous reports stating that environments with dense vegetation during summer are more effective at enhancing thermal comfort[23,41,42] and promoting physiological stability[43].

In the fall, significant differences were observed in all physical environmental factors, thermal comfort, subjective thermal sensation, and some physiological indicators. In the fall, the experimental site showed higher thermal comfort and subjective evaluation scores than the control site, resulting in physiological stability. These findings align with those of Massetti et al., who suggested that the shade of trees contributes to the

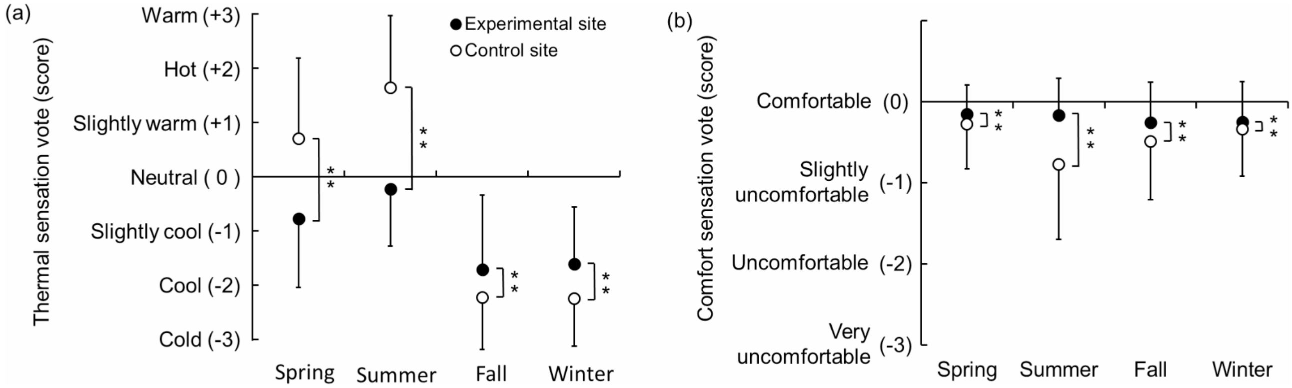

Fig. 6. Results of subjective evaluation; (**a**) thermal sensation vote, (**b**) comfort sensation vote. $N = 146$ (spring: $n = 40$; summer: $n = 31$; fall: $n = 39$; winter: $n = 36$). Analyzed by Wilcoxon signed-rank test, mean ± standard deviation. * $p < 0.05$, ** $p < 0.01$.

enhancement of thermal comfort[44]. It can be speculated that a physiological stability effect was induced, because the experimental site was thermally more comfortable than the control site.

The positive effects of the winter experimental site were attributed to the surrounding deciduous broad-leaved trees. Typically, shaded areas in winter are not thermally comfortable because of their lower temperatures. However, deciduous broadleaved trees allow solar radiation to pass through during winter by shedding their leaves, which can enhance thermal comfort[37]. Therefore, in this study, the winter experimental site appeared to be more thermally comfortable than the control site, with minimal differences in crown closure, facilitation of solar radiation, and wind blocking.

This study aimed to investigate the effects of seasonal changes in crown closure within broad-leaved forests on thermal comfort and human responses. Its significance lies in the comprehensive measurement and comparison of seasonal physical environmental factors, thermal comfort, and human physiological and psychological responses. However, this study has few limitations. Environments with relatively low temperatures and abundant shade may not provide high levels of thermal comfort when solar radiation is high. Furthermore, there may be discrepancies between the predicted thermal comfort and the subjective evaluation. Therefore, further studies in similar environments are necessary to resolve the interactions between these variables. In addition, visual and auditory stimuli that could influence physiological responses and subjective evaluations were not eliminated. Although the participants closed their eyes and wore earplugs during the rest periods, they were not entirely shielded from external stimuli because of the nature of the field experiment. Future research should consider minimizing the external stimuli as much as possible during the experiment. Moreover, in this study, only the average values during the 5-minute rest period were used for analysis. However, in future studies, it will be necessary to analyze in detail how the physiological response changes before and immediately after the visit, as well as during the rest period in both areas. A comprehensive analysis based on these data could help improve our understanding of human responses to changes in the environment and time points. Finally, all the participants in this study were male and female university students in their twenties, suggesting the need for broader investigations targeting diverse age groups and occupations. In the future, by recruiting more participants and continuously accumulating data on physical environmental factors, thermal comfort, and human physiological and psychological responses across various types of green spaces, research can aim to uncover the relationship among these elements. Additionally, studies should explore various perspectives, such as differences according to gender and age. From this viewpoint, the current study serves an important role as a foundational contribution to this field.

Conclusions

This study confirmed the seasonal differences in thermal comfort (PMV and PPD), physiological response (forehead temperature, blood pressure, pulse rate, heart rate, and heart rate variability), and personal thermal sensation (TSV and CSV) between forest areas with high (experimental site) and low (control site) crown closures. In summer, the experimental site exhibited significantly lower values of PMV, forehead temperature, diastolic blood pressure, pulse rate, and heart rate, and was subjectively evaluated as cooler and less unpleasant compared to the control site. In spring, the experimental site displayed significantly lower values of PMV and forehead temperature, while PPD values were significantly higher, and the site was subjectively perceived as cooler compared to the control site. During fall, PMV and forehead temperature values were significantly higher at the experimental site, while values of PPD and systolic and diastolic blood pressure were significantly lower, and the site was subjectively perceived as less cool and less unpleasant. In winter, the experimental site demonstrated significantly higher values of PMV and forehead temperature, significantly lower PPD values, and was subjectively perceived as less cool compared to the control site.

In conclusion, the experimental site appeared to be more effective than the control site in enhancing the thermal comfort, physiological stability, and subjective evaluation results in most seasons. Ultimately, this study confirmed that deciduous broad-leaved forests with high canopy closure are effective in enhancing thermal comfort, the subjective evaluation of thermal comfort, and physiological relaxation in most seasons.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Conceptualization, B.-J.P. and C.S.; methodology, J.K., I.S., C.K., B.-J.P. and C.S.; formal analysis, G.L., J.K. and I.S.; investigation, J.K., I.S., C.K. and C.S.; data curation, J.K., I.S., C.K. and D.J.; writing—original draft preparation, G.L.; writing—review and editing, D.J., B.-J.P. and C.S.; visualization, J.K. and G.L.; supervision, B.-J.P. and C.S.; project administration, B.-J.P. and C.S.; funding acquisition, B.-J.P. All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

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