forests

MDPI

Article

Thermal Comfort and Human Responses according to Tree Density in Forest Environments during and after Physical Activities in the Summer

Juhyeon Kim [1], Injoon Song [1], Choyun Kim [1], Hyejung Gho [2], Siok An [2], Doyun Song [2], Dawou Joung [2], Shinkwang Kang [3], Yunjeong Yi [4], Bum-Jin Park [2,*] and Chorong Song [1,*]

1 Department of Forest Science, Kongju National University, 54 Daehak-ro, Yesan-eup, Yesan-gun, Chungcheongnam-do 32439, Republic of Korea
2 Department of Forest Environment and Resources, Chungnam National University, Daejeon 34134, Republic of Korea
3 Department of Thoracic and Cardiovascular Surgery, Chungnam National University Hospital, Chungnam National University School of Medicine, Daejeon 35015, Republic of Korea
4 Department of Nursing, Kyung-In Women's University, Incheon 21041, Republic of Korea
* Correspondence: bjpark@cnu.ac.kr (B.-J.P.); crsong@kongju.ac.kr (C.S.); Tel.: +82-42-821-5746 (B.-J.P.); +82-41-330-1303 (C.S.); Fax: +82-42-825-7850 (B.-J.P.); +82-41-330-1308 (C.S.)

Abstract: This study aimed to comprehensively investigate the thermal comfort and physiological and psychological effects according to tree density in forest environments during rest and during and after physical activities in the summer. Participants consisted of 18 male university students (average age: 24.0 ± 1.6 years old), and a within-subjects experimental design was used. Participants sat on a chair for 5 min to rest, performed a step-box exercise for 8 min, and then sat on the chair again, and rested for 10 min in a forest with high tree density (85.6%) and one with low tree density (12.2% as a control). Thermal comfort (predicted mean vote; PMV and percentage of dissatisfied; PPD) and physiological and psychological responses were measured. We investigated and analyzed the changes in "rest", "during exercise", and "after exercise". As a result, a forest with high tree density showed a statistically significant decrease in PMV and PPD values; an increase in parasympathetic nervous activity; a decrease in respiratory rate, systolic blood pressure, and pulse rate; an improvement in mood state; an increase in comfortable, relaxed, and natural feelings; and more of an increase in personal thermal sensation during the recovery period after physical activities than in a forest with low tree density. In conclusion, a forest with high tree density during recovery after physical activities in the summer has higher thermal comfort and physiological and psychological relaxation effects on humans, as compared to one with low tree density.

Keywords: blood pressure; crown closure; forest density; heart rate variability; personal thermal sensation; percentage of dissatisfied; predicted mean vote; profile of mood states; relaxation; walk

Citation: Kim, J.; Song, I.; Kim, C.; Gho, H.; An, S.; Song, D.; Joung, D.; Kang, S.; Yi, Y.; Park, B.-J.; et al. Thermal Comfort and Human Responses according to Tree Density in Forest Environments during and after Physical Activities in the Summer. *Forests* **2023**, *14*, 120. https://doi.org/10.3390/f14010120

Academic Editor: Christos Gallis

Received: 6 December 2022
Revised: 23 December 2022
Accepted: 4 January 2023
Published: 9 January 2023

1. Introduction

Urbanization has brought about drastic changes. In modern residential spaces, the number of natural environments with multiple trees has decreased, and that of artificial structures, such as concrete buildings, has increased [1–3]. These changes have resulted in the urban heat island phenomenon, which refers to high temperatures caused by an increase in the internal temperature of a city area [4]. Due to the expansion of city areas and the increase in population density, the incidence of heat-related diseases, such as heatstroke, has increased [5]. The negative effects of a thermal environment on the human body have become a serious issue [5–8]. Additionally, a study reported that the prevalence and mortality rates are high in infants, children, and older adults [9]. This phenomenon is emerging worldwide as a constant public health concern [8]. Therefore, thermal environments must be improved at a national or global level, rather than on a personal level.

Urban forests play an important role in decreasing heat loads and maintaining a suitable temperature inside city areas through cooling effects [10–14]. According to a study examining the temperatures inside both urban green space and city area during the daytime, the average temperature in the urban green space was lower than that in the city area [10–14]. Recent studies have revealed that urban forests decrease not only the temperature, but also the thermal stress in urban areas. Lin et al. [15] studied the changes in thermal comfort in bamboo forests with four distinct seasons. In summer, the control sites had much stronger heat stress than the bamboo forest sites. Shashua-Bar et al. [16] compared thermal comfort among the shades of trees, trees covering grass, and mesh. The shade of trees covering grass had the least thermal stress than the shade of trees and shade of mesh. This finding suggests that urban green spaces are important for reducing thermal stress for city residents.

Furthermore, recent studies have reported that spending time in urban green spaces induces feelings of comfort in humans. Elsadek et al. [17] surveyed changes in thermal comfort and psychological responses when walking between urban roads surrounded by trees and without trees in the city. The participants evaluated that they had an improved mood state, felt less anxiety, had more vitality, and felt more restoration effects and thermal environment improved when walking under roadside trees. Park et al. [18] investigated differences in the comfortable feelings of thermal environments and the mood state between forests and urban areas. The participants evaluated that they felt more enjoyable, friendly, natural, and sacred, and had an improved mood state in the forest area than in the city area. Yoshida et al. [19] measured the thermal environment using thermal load and surveyed mood states while standing for 20 min under a tree canopy and in a sunlit place. Their findings indicated that the thermal environment improved, and negative mood states decreased under the tree canopy compared to sunlit places. Additionally, Gonçalves et al. [20] examined individuals' thermal sensations in four sites: over grass under the shade of a tree, over grass under artificial shade, over grass under direct solar radiation and near a wind shelter, and over the stone-paved ground under direct solar radiation. According to their results, people felt most comfortable with personal thermal sensations under the shade of a tree. This demonstrates that forested areas and green spaces provide thermal comfort.

Meanwhile, the quantity of solar radiation changes according to the type, shape, and density of trees, which causes a difference in thermal comfort [21,22]. Park et al. [23] researched physiological responses in forests with varying tree densities in summer and clarified that people were more physiologically relaxed in a forest with high tree density than in those of low tree density. Previous studies have investigated physical environmental factors, such as temperature and humidity, to evaluate thermal comfort, or only psychological reactions among human factors [15–23]. Comprehensive investigations of thermal environmental factors and physiological and psychological responses of the human body are lacking. In addition, most previous studies have focused on thermal comfort during stable activities, with insufficient research on dynamic activities. In practice, dynamic activities such as walking, spending time with children, and jogging constitute a large proportion of the motivation to visit and use natural environments [24]. Therefore, it is necessary to explore thermal comfort during rest and during and after physical activities.

This study aimed to comprehensively investigate thermal comfort and physiological and psychological relaxation effects according to tree density in forest environments during rest and during and after physical activities in the summer. Physical activity is relevant because it is directly related to thermal stress rather than stable activity. We investigated thermal comfort and physiological and psychological responses during and after dynamic activity, referred to as the YMCA step test, under the same environmental conditions. The results of this study can serve as a basis for guidelines for reducing thermal stress and improving comfort in the use of urban forests by urban residents in summer.

2. Materials and Methods

2.1. Participants

This study was approved by the Institutional Review Board (IRB number: CNU_IRB_202108-SB-181-0). Participants were recruited through a promotional leaflet. The study was conducted with those who expressed their intention to participate. Inclusion criteria were male university students in their 20s. Exclusion criteria were: (1) those who could not communicate, (2) those who were undergoing treatment for a disease, (3) those with a history of heart or cerebrovascular diseases, and (4) those who needed help going up and down the stairs. Eighteen male university students participated in this study. The demographic characteristics of the participants are provided in Table 1.

Table 1. Participant demographics (N = 18).

Parameter	Mean ± Standard Deviation
Age (years)	24.0 ± 1.6
Height (cm)	170.9 ± 4.8
Weight (kg)	69.5 ± 8.5
Body mass index (kg/m^2)	23.5 ± 2.5

Participants were instructed to sufficiently sleep the day before the experiment and were prohibited from consuming alcohol, tobacco, and caffeine. Consumption was controlled for two hours before the experiment period and during the experiment.

2.2. Experimental Sites

This study was conducted in a green space located in a university, which is most highly accessible to university students. Because the thermal environment is affected by the quantity of solar radiation, two experimental sites with different tree densities (high and low densities) were selected (Figure 1). Two experimental sites were approximately 79 m away, and there was no difference in latitude, elevation, and distance from buildings and roads. The ceilings of the sites were photographed using a fish-eye lens to measure tree density (Figure 2). Crown closure was analyzed using the Gap Light Analyzer program (Version 2.0, Copyright, Canada and USA). The crown closure in a forest with high tree density (hereafter referred to as high forest density) was 85.6% and one with low tree density (hereafter referred to as low forest density) was 12.2%. The temperature and humidity at the experimental sites on the day of the experiment are presented in Table 2.

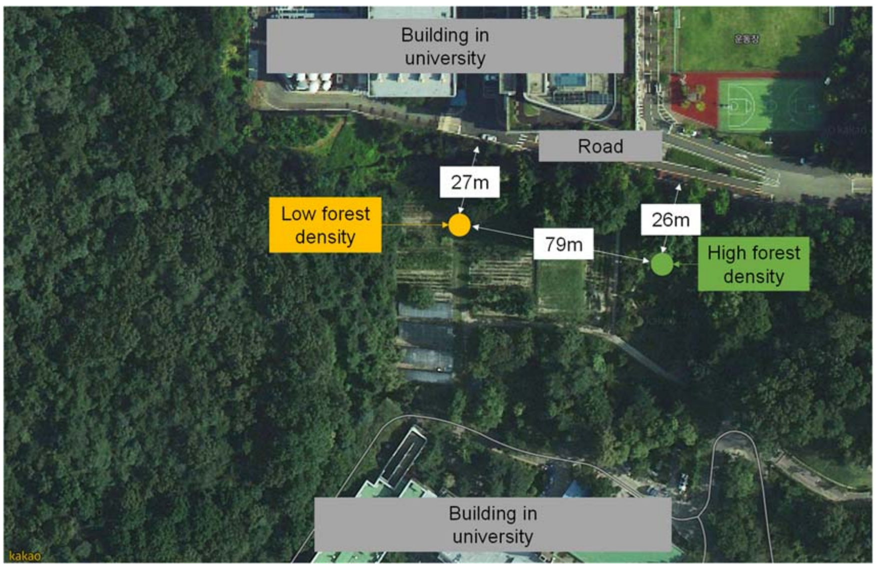

Figure 1. The location of the two experimental sites.

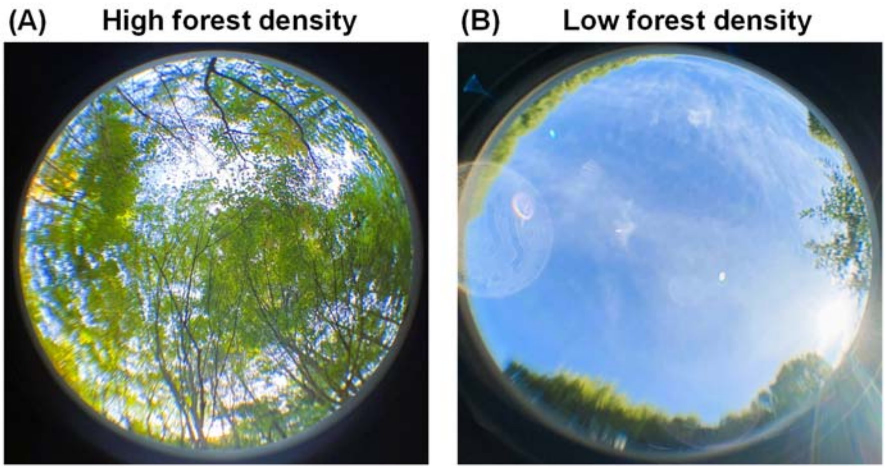

Figure 2. Photographs of high- and low-density forests.

Table 2. Temperature and humidity in the experimental site.

Experiment Date	15 September 2021		16 September 2021	
Experimental Site	High Forest Density	Low Forest Density	High Forest Density	Low Forest Density
Air temperature (°C) (mean ± SD [1])	26.1 ± 1.5	27.9 ± 1.8	24.3 ± 1.5	25.9 ± 1.3
Relative humidity (%) (mean ± SD)	55.3 ± 5.0	51.2 ± 4.0	63.9 ± 3.9	60.4 ± 3.4

[1] SD: Standard deviation.

2.3. Young Men's Christian Association (YMCA) Step Test

This study was conducted to measure the thermal comfort and physiological and psychological responses of the human body during physical activities. The crown closure changed when the participants walked. Thus, the Young Men's Christian Association (YMCA) step test, which was developed by Kasch [25] and designed to measure a person's aerobic fitness, was used (Figure 3). The YMCA step test involves a 30.5 cm high step box or bench. Participants were asked to step up and down on the step box or bench at a fixed pace of 24 steps/min [26].

Figure 3. The experimental scene.

2.4. Experimental Design

The experiments were conducted for two days, on 15 and 16 September 2021. The experimental design is illustrated in Figure 2. All participants were fully informed regarding the aims and procedures of this study and provided written consent to participate. They performed a step-test practice. Then, a device for measuring their heart rate variability (HRV) and heart rate (HR) was attached. The HRV and HR data were continuously measured throughout the experiment. This study adopted a within-subjects experimental design.

To eliminate the influence of the stimulus presentation sequence, participants were randomly divided into two groups. Participants who first performed the experiments in high forest density moved to low forest density and vice versa. After switching the experimental sites, the experiment was simultaneously conducted with the same procedure in different experimental locations. Participants were moved to each experimental site according to the experimenter's instructions. They sat down in their chairs and rested for 5 min (rest period in Figure 4).

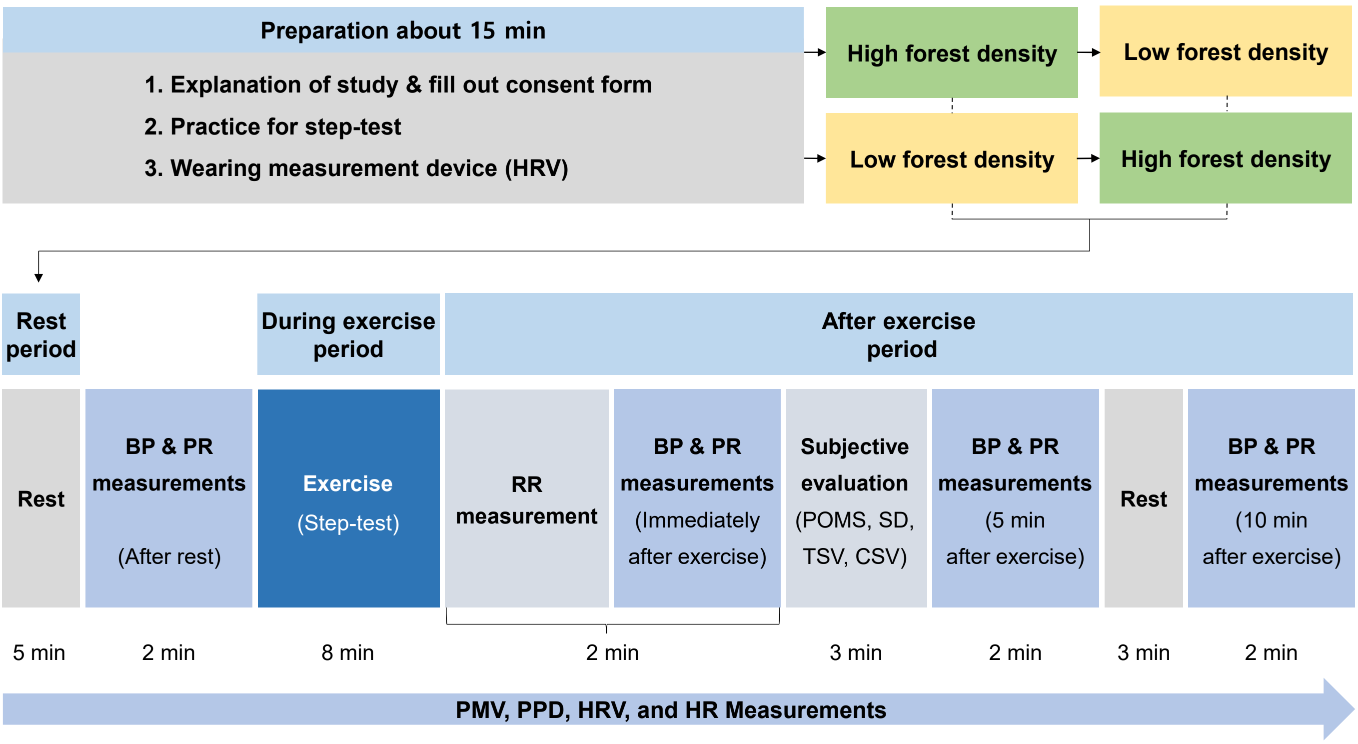

Figure 4. Experimental design. BP (blood pressure); CSV (comfort sensation vote); HRV (heart rate variability); PMV (predicted mean vote); POMS (profile of mood states); PPD (predicted percentage of dissatisfied); PR (pulse rate); RR (respiratory rate); SD (semantic differential); TSV (thermal sensation vote).

Thereafter, they performed a step test for 8 min (during the exercise period in Figure 2) with a metronome speed of 96 bits (24 times per min) using a step bench with a height of 30.5 cm. After the exercise (step-test), participants rested for 10 min (after the exercise period in Figure 4). The blood pressure and pulse rate were measured four times (after rest, immediately after exercise, 5 min after exercise, and 10 min after exercise). Respiratory rate measurements and subjective evaluations were performed "immediately after the exercise".

2.5. Environment Measurements

The predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) indices were used as indicators of thermal environment evaluation. PMV predicts the mean value of the votes of a large group of individuals, and it is rated on a 7-point thermal sensation scale (+3: hot, +2: warm, +1: slightly warm, 0: Neutral, −1: Slightly cool, −2: Cool, −3: Cold) [27]. PMV can be calculated for different combinations of metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity, and air humidity [28]. PPD is an indicator that establishes a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm [27]. In this study, PMV was calculated under the following conditions:

The metabolic rate was set at 1.0 met while sitting still and being at "rest" and 7.38 met "during exercise". These values were calculated using the following formula [29]:

$$VO_2 = (0.2 \cdot f) + (1.33 \cdot 1.8 \cdot H \cdot f) + 3.5, \quad (1)$$

VO_2: gross oxygen consumption in $mL \cdot kg^{-1} \cdot min^{-1}$,
f: stepping frequency in min^{-1},
H: step height in meters.

$$1 \text{ met} = 3.5\ VO_2 \text{ kg/min} \quad (2)$$

The clothing insulation was set to 0.5 clo (underpants, shirt with short sleeves, light trousers, light socks, and shoes), which is appropriate for summer wear [28]. This study measured thermal environment evaluation indicators, such as air temperature, mean radiant temperature, air velocity, and air humidity using a portable weather meter (Kestrel 5400, Nielsen Kellerman Corporation, Boothwyn, PA, USA).

2.6. Physiological Measurements

2.6.1. Heart Rate Variability and Heart Rate

Heart rate variability (HRV) is a method used to measure the autonomic nervous system by measuring periods between consecutive R waves (R-R intervals) [30]. This study was performed using a wearable electrocardiogram sensing system (myBeat; Union Tool Co., Tokyo, Japan). Additionally, we used the maximum entropy method (MemCalc/Win software, GMS, Japan) to determine the power of the low-frequency (LF; 0.04–0.15 Hz) and high-frequency (HF; 0.15–0.40 Hz) components of HRV [31]. The HF component of HRV reflects parasympathetic nervous activity, which indicates more physiologically relaxed states. A higher LF/HF ratio reflects sympathetic nervous activity, which means more physiologically tense or stressed states [32]. In this study, we used natural logarithmic-transformed values to normalize HRV parameters across the participants [33]. The heart rate was also measured using myBeat for the number of heart beats per min.

2.6.2. Respiratory Rate

Respiratory rate refers to the number of breaths taken per min. This was measured for 30 s by recognizing the movement of the chest when each participant inhaled and exhaled. Subsequently, it was calculated for 60 s by doubling.

2.6.3. Blood Pressure and Pulse Rate

Systolic blood pressure, diastolic blood pressure, and pulse rate were measured using an oscillometric method with a digital blood pressure monitor (P2100 model, Terumo, Tokyo, Japan).

2.7. Physiological Measurements

2.7.1. Profile of Mood States

Profile of mood states (POMS) is a questionnaire for evaluating of a person's mood state [34]. POMS simultaneously evaluates six moods: tension and anxiety (T-A), depression and dejection (D), anger and hostility (A-H), fatigue (F), confusion (C), and vigor (V). The total mood disturbance (TMD) score was calculated using the formula "T-A" + "D" + "A-H" + "F" + "C" − "V". The higher the score, the more negative the feeling.

This study used the Korean version of the brief POMS (K-POMS-B) with 30 questions and rated on a 4-point scale. This method was translated into Korean by Yeun and Shin-Park [35].

2.7.2. Semantic Differential Method

The semantic differential (SD) method [36] is a questionnaire for evaluating the impressions of objects using adjectives that express emotions. In this study, the following three pairs of adjectives were assessed on a 13-point scale: "comfortable-uncomfortable", "relaxed-aroused", and "natural-artificial".

2.7.3. Thermal Sensation Vote and Comfort Sensation Vote

Personal thermal sensation was surveyed using the thermal sensation vote (TSV) and comfort sensation vote (CSV) [37]. The TSV represents subjective warmth and is rated on a 7-point scale ranging from "hot" to "cold". CSV represents subjective comfort and is evaluated using a 4-point scale ranging from "comfortable" to "very uncomfortable".

2.8. Data Analysis

In total, 18 participants were included in our study. However, one participant was excluded because of continuous sneezing during the physiological evaluation. Five more participants were excluded because we were unable to analyze their HRV data.

Further, one of the eighteen participants was excluded because he missed one question in the psychological evaluation of the POMS.

Statistical analyses were performed using SPSS 27.0 (IBM Corp., Armonk, NY, USA). Independent *t*-tests were used for the thermal environment evaluation of the experimental site, paired *t*-tests were used for physiological evaluation, and Wilcoxon signed-rank tests were used for psychological evaluation. For all analyses, a p-value < 0.05 was considered statistically significant. This study used a one-sided test because we hypothesized that based on previous studies, high tree density during recovery after exercise in summer indicates a higher thermal comfort, as well as physiological and psychological relaxation effects on humans [17–20,23].

3. Results

3.1. Environment Measurements

Figure 5 shows the time-dependent shifts in PMV values per min. PMV values in high forest density were lower than those in low forest density during entire periods, including "rest", "during exercise", and "after exercise". As a result of the statistical analysis, the mean values of each period (high forest density: 0.1 ± 0.7 (mean $\pm$ standard deviation) vs. low forest density: 1.9 ± 1.5 in "rest"; high: 7.1 ± 0.3 vs. low: 8.2 ± 0.7 in "during exercise"; high: 0.1 ± 0.6, low: 1.8 ± 1.2 in "after exercise") were significantly lower in high forest density than in low forest density ($p < 0.01$, Figure 5B).

Figure 6 shows the time-dependent shifts in PPD values per min. PPD values were also lower in high forest density than in low forest density for "rest" and "after exercise" periods (Figure 6A). As a result of the statistical analysis, the mean values of each period (high: $15.3 \pm 11.1\%$ vs. low: $54.0 \pm 29.3\%$ in "rest"; high: $12.7 \pm 7.0\%$ vs. low: $56.7 \pm 29.1\%$ in "after exercise") were significantly lower in high forest density than in low forest density ($p < 0.01$, Figure 6B). However, a significant difference was not detected for "during exercise" (high: $100.0 \pm 0.0\%$ vs. low: $100.0 \pm 0.0\%$; Figure 6B).

3.2. Physiological Measurements

3.2.1. Heart Rate Variability and Heart Rate

Figure 7A shows the time-dependent shifts in ln(HF) values per min, which is an indicator of parasympathetic nervous activity. There were no differences between "rest" and "during exercise" periods. However, ln(HF) values increased faster in high forest density than in low forest density from 2 min "after exercise" (15 min in the Figure 7A).

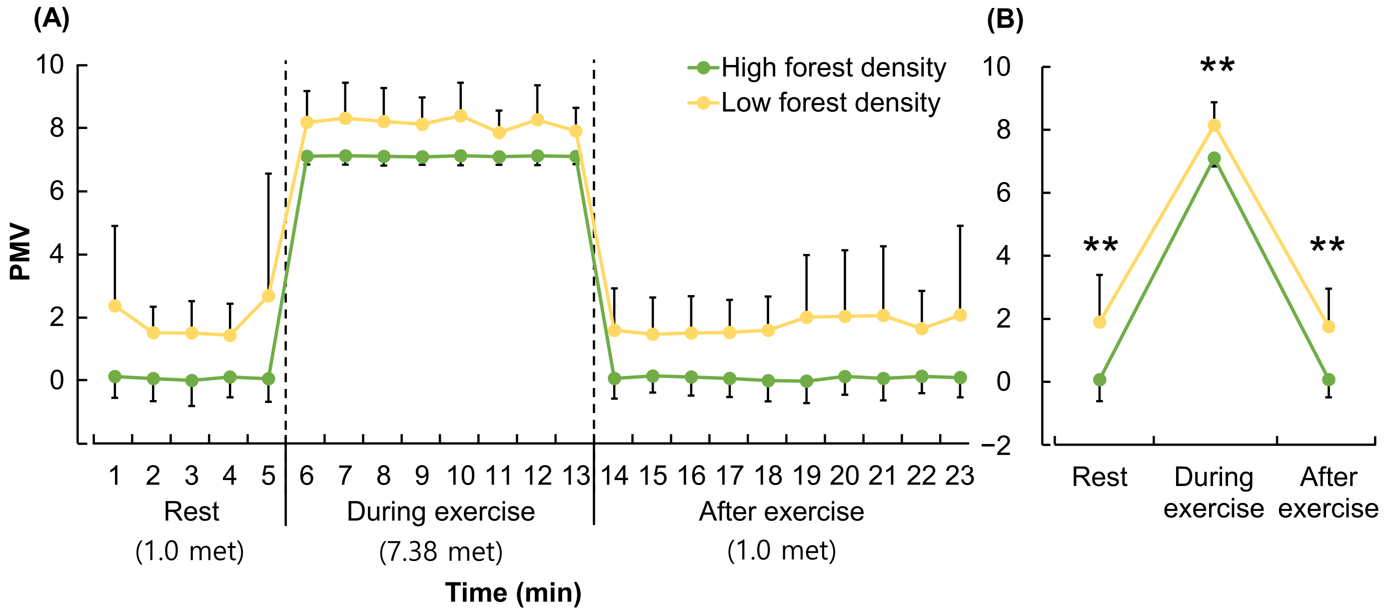

Figure 5. Changes in the predicted mean vote (PMV) between high forest density and low forest density. (**A**) Time-dependent changes in PMV N = 18, mean ± standard deviation. (**B**) Overall mean PMV in the “rest”, “during exercise”, and “after exercise” periods. N = 18, mean ± standard deviation; ** $p < 0.01$ using the independent t-test.

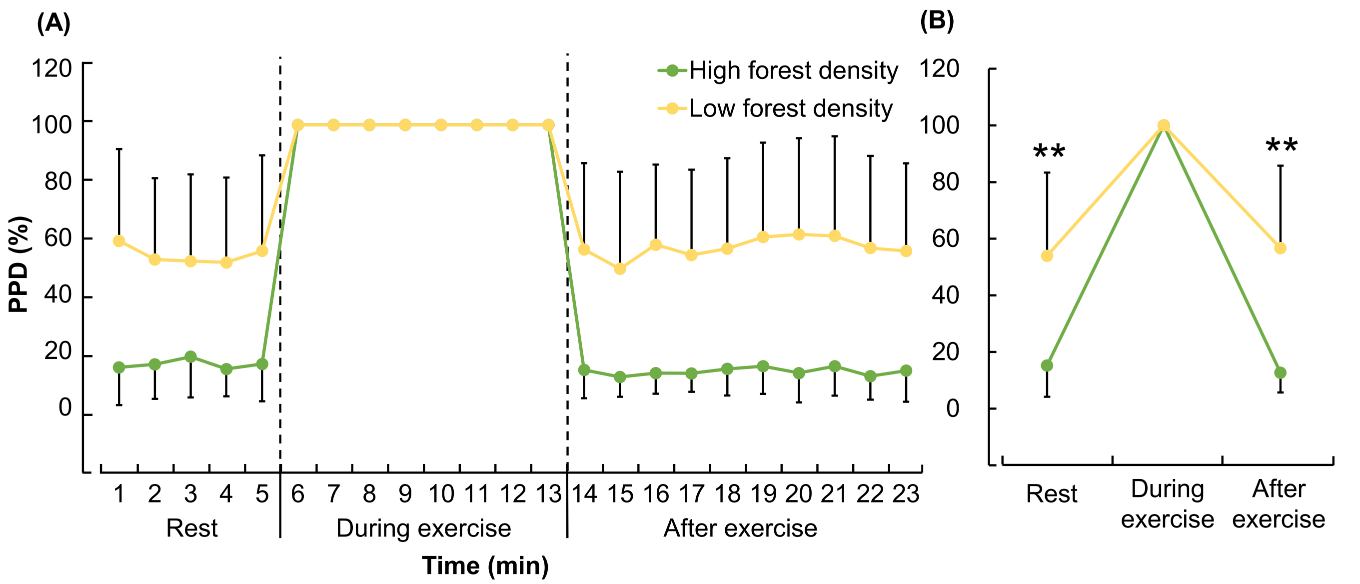

Figure 6. Changes in the predicted percentage of dissatisfied (PPD) between high forest density and low forest density. (**A**) Time-dependent changes in PPD. N = 18, mean ± standard deviation. (**B**) Overall mean PPD in the “rest”, “during exercise”, and “after exercise” periods. N = 18, mean ± standard deviation; ** $p < 0.01$ using the independent t-test.

As a result of the statistical analyses for each period, a significant difference was observed in “after exercise”. The ln(HF) values were significantly higher in high forest density than in low forest density (high: 2.85 ± 0.37 lnms^2 (mean ± standard error) vs. low: 2.37 ± 0.38 lnms^2, $p < 0.05$, Figure 7C). No significant differences were observed for the ln(LF/HF) ratio and HR.

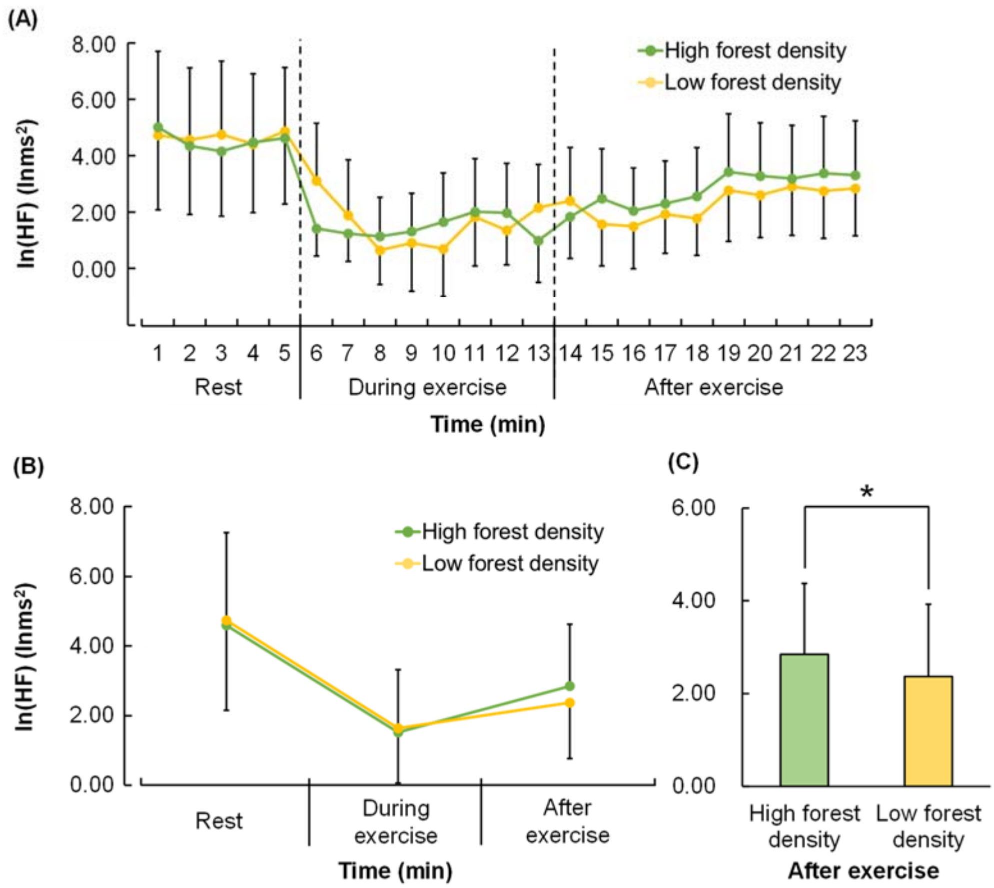

Figure 7. Changes in ln(HF) values of heart rate variability between high forest density and low forest density. It is divided into three periods: "rest", "during exercise", and "after exercise". (**A**) Changes in each 1-min average ln(HF) values over the 23-min experiment. N = 12, mean ± standard error. (**B**) Changes in the average ln(HF) values in the three periods. N = 12, mean ± standard error. (**C**) Comparison of mean ln(HF) values "after exercise". N = 12, mean ± standard error. * $p < 0.05$ using the paired t-test.

3.2.2. Respiratory Rate

Figure 8 shows the results of the respiratory rate "after exercise", which showed a significant difference (high: 26.5 ± 1.2 breaths/min vs. low: 28.5 ± 1.3 breaths/min; $p < 0.05$, Figure 8). The respiratory rate was lower in high forest density than in low forest density "after exercise".

3.2.3. Blood Pressure and Pulse Rate

There was a significant difference in diastolic blood pressure (high: 69.1 ± 3.2 mmHg vs. low: 63.5 ± 2.8 mmHg; $p < 0.05$) "after rest". Therefore, the changes were calculated based on the value obtained "after rest" and were compared between all periods.

Figure 9 shows the changes in systolic blood pressure. The systolic blood pressure was lower in high forest density than in low forest density (Figure 9A). As a result of statistically analyzing the average for each period, significant differences were observed in "immediately after exercise" (high: 34.5 ± 3.1 mmHg vs. low: 41.8 ± 3.9 mmHg, $p < 0.05$, Figure 9B) and in "10 min after exercise" (high: −2.2 ± 2.1 mmHg vs. low: 3.8 ± 2.2 mmHg, $p < 0.05$, Figure 9C). For the diastolic blood pressure, no significant difference was detected.

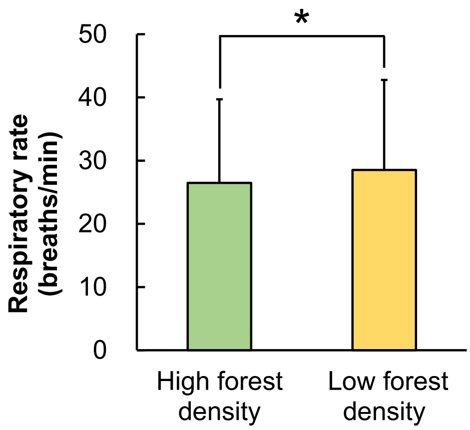

Figure 8. Effect on the respiratory rate "after exercise" between high forest density and low forest density. N = 17, mean ± standard error. * $p < 0.05$ using the paired *t*-test.

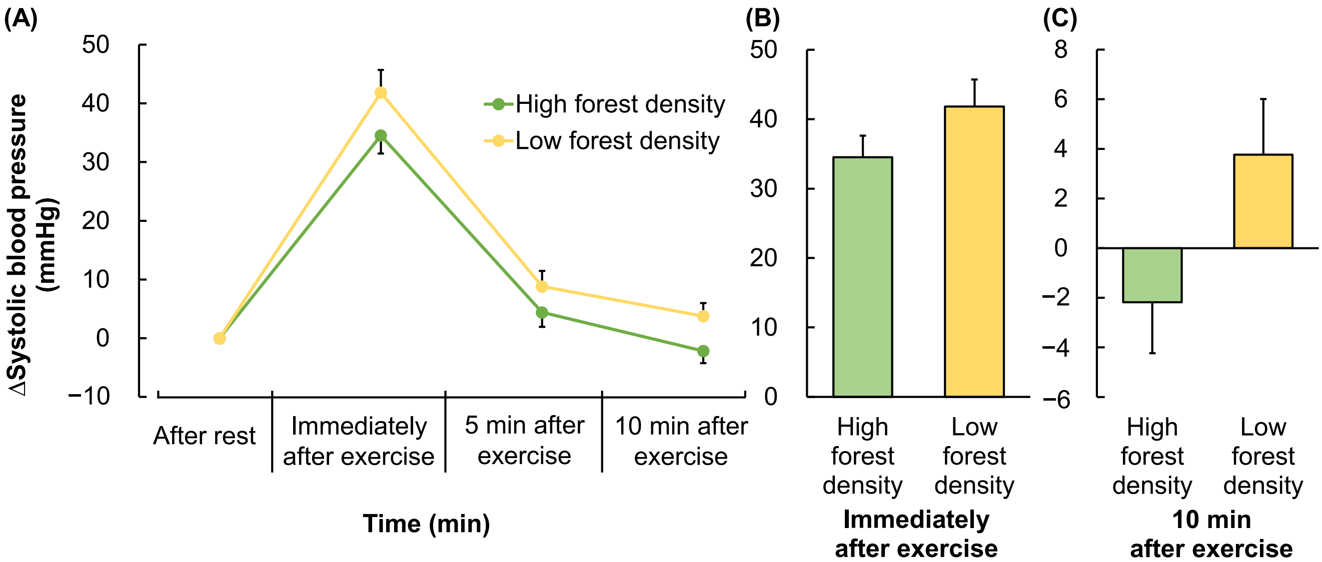

Figure 9. Average systolic blood pressure of blood pressure between high forest density and low forest density. (**A**) Changes in four periods on average systolic blood pressure frequency. N = 17, mean ± standard error. (**B**) Effect on systolic blood pressure frequency in "immediately after exercise". N = 17, mean ± standard error. * $p < 0.05$ using the paired *t*-test. (**C**) Effect on systolic blood pressure frequency "10 min after exercise" N = 17, mean ± standard error. * $p < 0.05$ using the paired *t*-test.

Figure 10 shows the changes in pulse rate. The pulse rate was lower in high forest density than in low forest density for all periods (Figure 10A). After statistically analyzing the average for each period, significant differences were detected in "immediately after exercise" (high: 37.1 ± 3.2 bpm vs. low: 45.5 ± 3.4 bpm; $p < 0.05$, Figure 10B). The pulse rate was significantly lower in high forest density than in low forest density. For diastolic blood pressure, no significant difference was observed.

3.3. Psychological Measurements

3.3.1. Profile of Mood States

Figure 11 shows the results of the POMS. A significant difference was observed in T-A, D, A-H, F, C, and V in both high and low forest densities "after exercise".

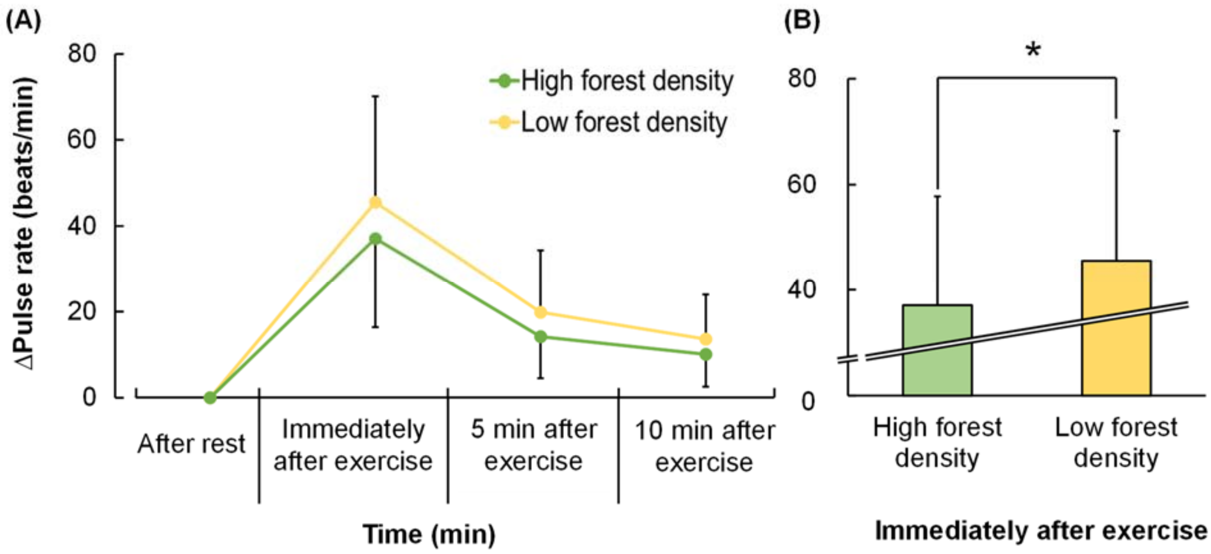

Figure 10. The average pulse rate of blood pressure between high forest density and low forest density. (**A**) Changes in the four periods of average pulse rate frequency. N = 17, mean ± standard error. (**B**) Effect on pulse rate frequency in "after exercise". N = 17, mean ± standard error. * $p < 0.05$ using the paired *t*-test.

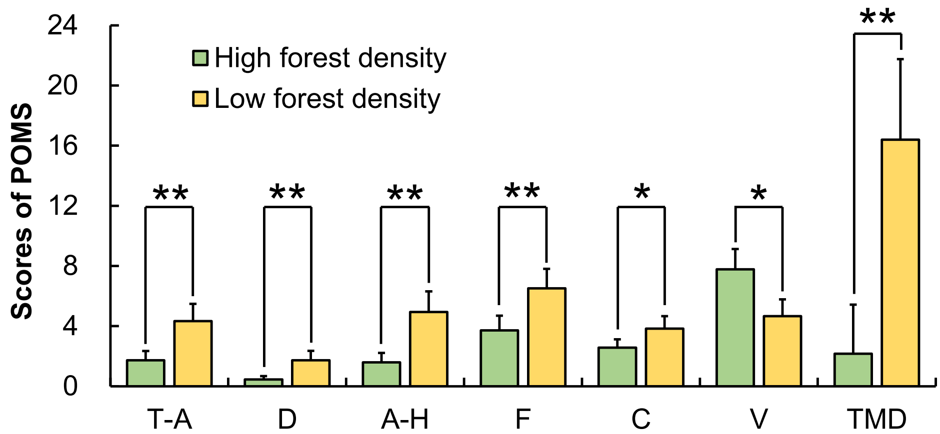

Figure 11. Comparison of profile of mood state (POMS) scores in the "after exercise" between high forest density and low forest density. T-A, tension-anxiety; D, depression; A-H, anger-hostility; F, fatigue; C, confusion; V, vigor; TMD, total mood disturbance. N = 17–18, mean ± standard error. * $p < 0.05$, ** $p < 0.01$ using the Wilcoxon signed-rank test.

The subscale scores in high forest density and low forest density were as follows: tension and anxiety, 1.7 ± 0.6 vs. 4.3 ± 1.1; depression and dejection, 0.4 ± 0.2 vs. 1.7 ± 0.6; anger and hostility, 1.6 ± 0.6 vs. 4.9 ±1.4; fatigue, 3.7 ± 1.0 vs. 6.5 ± 1.3; and confusion, 2.6 ± 0.6 vs. 3.8 ± 0.8. A decrease in negative mood states was observed in high forest density than in low forest density "after exercise" ($p < 0.05$, $p < 0.01$, Figure 11). In contrast, the score for vigor, a positive mood state, was significantly higher in high forest density than in low forest density (high: 7.8 ± 1.3 vs. low: 4.7 ± 1.1; $p < 0.05$, Figure 11). The TMD was significantly lower in high forest density than in low forest density (high: 2.2 ± 3.3 vs. low: 16.4 ± 5.4; $p < 0.01$, Figure 11).

3.3.2. Semantic Differential Method

Figure 12 shows the results of using the SD method. The participants felt more comfortable (high: 0.9 ± 0.6 vs. low: −2.3 ± 0.8; $p < 0.01$, Figure 12), relaxed (high:

3.1 ± 0.5 vs. low: 0.3 ± 0.8; p < 0.01, Figure 12), and natural (high: 1.9 ± 0.5 vs. low: −0.9 ± 0.7; $p < 0.01$, Figure 12) in high forest density than in low forest density "after exercise".

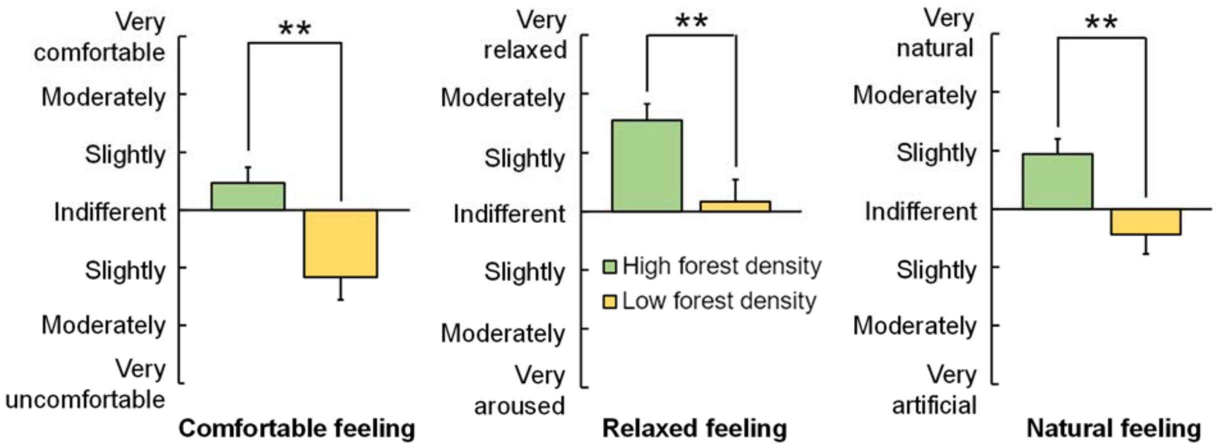

Figure 12. Comparison of semantic differential (SD) method scores in the "after exercise" between high forest density and low forest density. Changes in the subjective feelings of "comfortable", "relaxed", and "natural". N = 18, mean ± standard error. ** $p < 0.01$ using the Wilcoxon signed-rank test.

3.3.3. Thermal Sensation Vote and Comfort Sensation Vote

Figure 13 shows the results of the personal thermal sensation and comfort sensation votes. Significant differences were observed in the TSV (high: 1.2 ± 0.3 vs. low: 2.6 ± 0.3; $p < 0.01$; Figure 13) and CSV (high: −1.0 ± 0.1 vs. low: −1.9 ± 0.3; $p < 0.01$, Figure 13) "after exercise". The thermal sensation vote score was significantly lower in high forest density than in low forest density, and the feeling of discomfort was significantly lower in high forest density than in low forest density.

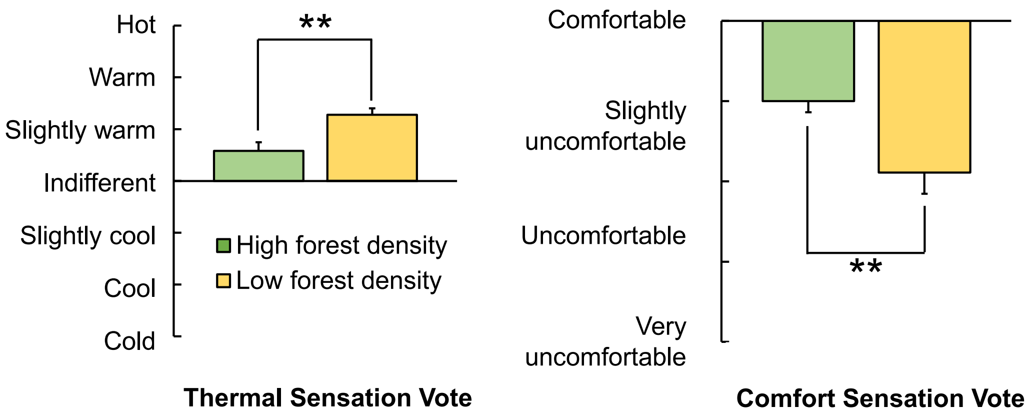

Figure 13. Comparison of thermal sensation vote (TSV) and comfort sensation vote (CSV) scores in the "after exercise" between high forest density and low forest density. Changes in the personal sensations of "Thermal" and "Comfort". N = 18, mean ± standard error. ** $p < 0.01$ using the Wilcoxon signed-rank test.

4. Discussion

The purpose of this study was to comprehensively reveal the thermal comfort as well as physiological and psychological effects on humans in forest environments with varying tree densities during rest and during and after physical activities in the summer. This study demonstrated that thermal comfort and physiological and psychological relaxation effects were higher in high forest density than in low forest density when taking a rest during the "after exercise" period.

The thermal comfort results are as follows: The PMV values were significantly lower in high forest density during the entire period. As the values were closer to zero, this meant that the participants felt more thermally comfortable. PPD values were significantly lower in high forest density during “rest” and “after exercise”. This reveals that thermal comfort in summer is higher in high forest density than in low forest density. These results were partially consistent with those of a previous study. Park et al. [18] compared thermal comfort between forest and city areas while standing in the summer. According to their results, PMV values in the forest were significantly lower during forenoon (10:00–13:00) than in the city areas, but there was no significant difference with afternoon (13:00–16:00). The PPD values in the forest were significantly lower during the forenoon and afternoon (11:00–16:00) than in the city areas. In contrast, there was no significant difference detected “during exercise” in our study; we consider that the difference in PPD results with the previous study occurred due to the difference in metabolic rates. In the previous study, the metabolic rate while standing was 2.0 met. In the present study, the metabolic rate while walking was 7.38 met. In this study, the PPD values were 100% in both experimental sites “during exercise” because the intensity of physical activities was very high. Therefore, our study focused on recovery effects after physical activities.

Recent studies have reported that thermal comfort can change within forest environments due to structural differences. Park et al. [23] surveyed the thermal comfort and physiological responses of 15 men and women in their 20s in *Pinus koraiensis* forests with different tree densities in summer and revealed that a forest with high tree densities had lower PMV and PPD and higher HF values. Kim et al. [38] investigated the thermal comfort that varies depending on the difference in crown closure inside the urban green area. The place with 100% crown closure had lower PPD compared to other low crown closure places. Considering the appropriate tree density when creating and managing urban green areas can play an important role in improving the thermal comfort of users.

The results of the physiological measurements are as follows: ln(HF) was significantly higher in high forest density than in low forest density “after exercise”. Systolic blood pressure, pulse rate, and respiratory rate were significantly lower “immediately after exercise” and/or “10 min after exercise” in high forest density than in low forest density. Numerous studies have examined the physiological effects of these activities in forest environments. Song et al. [39] examined the physiological response of 12 female university students when walking in the forest and city area. They revealed higher parasympathetic nervous activity, lower sympathetic nervous activity, and decreased heart rate when walking in the forest than when walking in the city area. Lee et al. [40] demonstrated that when 48 male university students walked in the forest and urban areas, forest walking increased parasympathetic nervous activity and decreased sympathetic nervous activity. Furthermore, Park et al. [41] demonstrated that systolic and diastolic blood pressure were significantly lower after walking in a forest environment than in a city area. Our findings revealed that, compared with an area of forest with low tree density, an area with high tree density had the effects of reducing blood pressure and pulse rate, even within the same forest environment. Furthermore, we found that while blood pressure and pulse rate increased “immediately after exercise”, these had declined when measured at “5 and 10 min after exercise”, falling to values within the normal respective ranges. Therefore, these findings indicate the importance of forest environments in promoting post-exercise recovery.

The results of the psychological evaluation were as follows: Negative mood states were lower and positive mood states were higher in high forest density than in low forest density. Comfortable, relaxed, and natural feelings were higher in high forest density than in low forest density. Additionally, personal thermal comfort sensation was better in high forest density than in low forest density. The results of this study are consistent with those of several previous studies [42–44]. Takayama et al. [42] revealed that 11 to 12 male university students had significantly lower tension and anxiety, depression, and confusion after walking in the forest compared to before walking in the forest. Song et al. [43] demonstrated that comfortable, relaxed, and natural feelings increased while walking in a forest environment, which indicates psychological relaxation. Kobayashi et al. [44] compared the psychological responses of 57 female university students when walking and viewing in a forest environment. In the forest environment, vigor was significantly higher during walking than during viewing, and fatigue and confusion were significantly lower. Our study reported that participants experienced psychological relaxation more in high forest density than in low forest density.

We revealed that the thermal comfort and physiological and psychological relaxation effects after physical activities in summer were higher in a forest with high tree density than in those with low tree density. Previous studies have investigated physical environmental factors, such as temperature and humidity, to evaluate thermal comfort, or only psychological reactions among human factors [15–20,23]. Comprehensive investigation of physical environmental factors and physiological and psychological responses of the human body is lacking. In outdoor activities in summer, how thermal comfort is generated when controlling the density of standing trees in urban forests and how humans are affected should be comprehensively reviewed.

People visit urban green spaces to enjoy the weather and obtain fresh air by escaping from artificial structures [45]. Home et al. [24] reported that the purposes of visiting urban green spaces were walking (79.4%), spending time with children (43.5%), and cycling (35.3%), among others. Urban green spaces can be used as healing spaces to increase thermal comfort and induce physiological and psychological relaxation by reducing the thermal stress on people. This study is meaningful for investigating the difference in the recovery effect according to the passage of time after physical activities in different forest densities. These results suggest that if an urban green space were provided to reduce thermal stress in summer, urban residents would safely use it. Proper physical activities in urban forests can help prevent various diseases caused by lack of exercise and stress management in daily life. This has value from the perspective of preventive medicine and can help reduce medical costs.

5. Conclusions

This study aimed to comprehensively investigate the thermal comfort and physiological and psychological effects according to tree density in forest environments during rest and during and after physical activities in the summer. Compared to a forest with low tree density, in a forest with high tree density: (1) PMV and PPD values were lower; (2) parasympathetic nervous activity was enhanced, but respiratory rate, diastolic blood pressure, and pulse rate were lower; (3) participants' mood states were improved, and they felt more "comfortable", "relaxed", and "natural"; (4) participants' personal thermal sensation was improved. In conclusion, a forest with high tree density during recovery after physical activities in the summer induces higher thermal comfort and physiological and psychological relaxation effects in humans.

Nonetheless, this study has some limitations. First, the participants were limited to male university students in their 20s. To generalize our results, future studies should include different age groups along with those in their 20s and female participants. Second, the tree species at the experimental sites were different. Future studies are necessary to verify the effects of density differences in forest environments consisting of the same tree species. This is because it is believed that there will be differences in thermal comfort and physiological and psychological responses depending on the types of trees that make up the forest, such as coniferous and broad-leaved species or a mixture of these two types. An experiment conducted in a forest comprising a single tree species would enable us to more clearly determine the effects of tree density. Finally, the measurements were only performed in summer, and other seasons were not examined. Future studies should conduct experiments not only in summer, but also in other seasons.

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

Funding: This research was funded by Korea Forestry Promotion Institute, grant number 2021386A00-2123-0101.

Data Availability Statement: Data are contained within the article and are also available from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Nuruzzaman, M. Urban heat island: Causes, effects and mitigation measures-a review. *Int. J. Environ. Monit. Anal.* **2015**, *3*, 67–73. [CrossRef]
2. Mohajerani, A.; Bakaric, J.; Jeffrey–Bailey, T. The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *J. Environ. Manag.* **2017**, *197*, 522–538. [CrossRef] [PubMed]
3. Sun, L.; Chen, J.; Li, Q.; Huang, D. Dramatic uneven urbanization of large cities throughout the world in recent decades. *Nat. Commun.* **2020**, *11*, 5366. [CrossRef] [PubMed]
4. Yow, D.M. Urban heat islands: Observations, impacts, and adaptation. *Geogr. Compass* **2007**, *1*, 1227–1251. [CrossRef]
5. Lowe, S.A. An energy and mortality impact assessment of the urban heat island in the US. *Environ. Impact Assess. Rev.* **2016**, *56*, 139–144. [CrossRef]
6. D'Ippoliti, D.; Michelozzi, P.; Marino, C.; de'Donato, F.; Menne, B.; Katsouyanni, K.; Kirchmayer, U.; Analitis, A.; Medina-Ramón, M.; Paldy, A. The impact of heat waves on mortality in 9 European cities: Results from the EuroHEAT project. *Environ. Health* **2010**, *9*, 37. [CrossRef]
7. Bai, L.; Ding, G.; Gu, S.; Bi, P.; Su, B.; Qin, D.; Xu, G.; Liu, Q. The effects of summer temperature and heat waves on heat-related illness in a coastal city of China, 2011–2013. *Environ. Res.* **2014**, *132*, 212–219. [CrossRef]
8. Vaidyanathan, A.; Malilay, J.; Schramm, P.; Saha, S. Heat-related deaths? United States, 2004–2018. *Morb. Mortal. Wkly. Rep.* **2020**, *69*, 729. [CrossRef]
9. Basu, R. High ambient temperature and mortality: A review of epidemiologic studies from 2001 to 2008. *Environ. Health* **2009**, *8*, 40. [CrossRef]
10. Chang, C.R.; Li, M.H. Effects of urban parks on the local urban thermal environment. *Urban For. Urban Green.* **2014**, *13*, 672–681. [CrossRef]
11. Perini, K.; Magliocco, A. Effects of vegetation, urban density, building height, and atmospheric conditions on local temperatures and thermal comfort. *Urban For. Urban Green.* **2014**, *13*, 495–506. [CrossRef]
12. Yan, H.; Wu, F.; Dong, L. Influence of a large urban park on the local urban thermal environment. *Sci. Total Environ.* **2018**, *622*, 882–891. [CrossRef] [PubMed]
13. Quaranta, E.; Dorati, C.; Pistocchi, A. Water, energy and climate benefits of urban greening throughout Europe under different climatic scenarios. *Sci. Rep.* **2021**, *11*, 12163. [CrossRef]
14. Bowler, D.E.; Buyung-Ali, L.; Knight, T.M.; Pullin, A.S. Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landsc. Urban Plan.* **2010**, *97*, 147–155. [CrossRef]
15. Lin, W.; Zeng, C.; Lam, N.S.; Liu, Z.; Tao, J.; Zhang, X.; Lyu, B.; Li, N.; Li, D.; Chen, Q. Study of the relationship between the spatial structure and thermal comfort of a pure forest with four distinct seasons at the microscale level. *Urban For. Urban Green.* **2021**, *1*, 127168. [CrossRef]
16. Shashua-Bar, L.; Pearlmutter, D.; Erell, E. The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. *Int. J. Climatol.* **2011**, *31*, 1498–1506. [CrossRef]
17. Elsadek, M.; Liu, B.; Lian, Z.; Xie, J. The influence of urban roadside trees and their physical environment on stress relief measures: A field experiment in Shanghai. *Urban For. Urban Green.* **2019**, *1*, 51–60. [CrossRef]
18. Park, B.J.; Furuya, K.; Kasetani, T.; Takayama, N.; Kagawa, T.; Miyazaki, Y. Relationship between psychological responses and physical environments in forest settings. *Landsc. Urban Plan.* **2011**, *102*, 24–32. [CrossRef]
19. Yoshida, A.; Hisabayashi, T.; Kashihara, K.; Kinoshita, S.; Hashida, S. Evaluation of effect of tree canopy on thermal environment, thermal sensation, and mental state. *Urban Clim.* **2015**, *14*, 240–250. [CrossRef]
20. Gonçalves, A.; Castro Ribeiro, A.; Maia, F.; Nunes, L.; Feliciano, M. Influence of green spaces on outdoors thermal comfort—Structured experiment in a mediterranean climate. *Climate* **2019**, *7*, 20. [CrossRef]

21. Milošević, D.D.; Bajšanski, I.V.; Savić, S.M. Influence of changing trees locations on thermal comfort on street parking lot and footways. *Urban For. Urban Green.* **2017**, *23*, 113–124. [CrossRef]
22. Liu, H.; Lim, J.Y.; Thet, B.W.; Lai, P.Y.; Koh, W.S. Evaluating the impact of tree morphologies and planting densities on outdoor thermal comfort in tropical residential precincts in Singapore. *Build. Environ.* **2022**, *8*, 109268. [CrossRef]
23. Park, B.J.; Kyeon, C.; Choi, Y.; Yeom, D.G.; Kim, G.; Joung, D. The effect of tree density of Pinus koraiensis forest on the thermal comfort and the physiological response of human body in summer season. *J. Korean Soc. For. Sci.* **2015**, *104*, 261–266. (In Korean, with English abstract). [CrossRef]
24. Home, R.; Hunziker, M.; Bauer, N. Psychosocial outcomes as motivations for visiting nearby urban green spaces. *Leis. Sci.* **2012**, *34*, 350–365. [CrossRef]
25. Kasch, F.W. A comparison of the exercise tolerance of post-rheumatic and normal boys. *J. Assoc. Phys. Mental Rehabil.* **1961**, *15*, 35–40.
26. Golding, L.A. *YMCA Fitness Testing and Assessment Manual*, 4th ed.; Young Men's Christian Association: Chicago, IL, USA, 2000.
27. Fanger, P.O. *Thermal Comfort. Analysis and Applications in Environmental Engineering*; Danish Technical Press: Copenhagen, Denmark, 1970.
28. ISO I. 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. *Management* **2005**, *3*, 605–615.
29. American College of Sports Medicine. METABOLIC CALCULATIONS. In *ACSM's Guidelines for Exercise Testing and Prescription*, 6th ed.; Pescatello, L.S., Riebe, D., Thompson, P.D., Eds.; Lippincott Williams & Wilkins: Philadelphia, PA, USA, 2013.
30. Kobayashi, H.; Ishibashi, K.; Noguchi, H. Heart rate variability; an index for monitoring and analyzing human autonomic activities. *Appl. Hum. Sci.* **1999**, *18*, 53–59. [CrossRef]
31. Kanaya, N.; Hirata, N.; Kurosawa, S.; Nakayama, M.; Namiki, A. Differential effects of propofol and sevoflurane on heart rate variability. *J. Am. Soc. Anesthesiol.* **2003**, *98*, 34–40. [CrossRef]
32. Cacioppo, J.T.; Berntson, G.G.; Binkley, P.F.; Quigley, K.S.; Uchino, B.N.; Fieldstone, A. Autonomic cardiac control. II. Noninvasive indices and basal response as revealed by autonomic blockades. *Psychophysiology* **1994**, *31*, 586–598. [CrossRef]
33. Kobayashi, H.; Park, B.J.; Miyazaki, Y. Normative references of heart rate variability and salivary alpha-amylase in a healthy young male population. *J. Physiol. Anthropol.* **2012**, *31*, 9. [CrossRef]
34. McNair, D.M.; Lorr, M. An analysis of mood in neurotics. *J. Abnorm. Soc. Psychol.* **1964**, *69*, 620. [CrossRef] [PubMed]
35. Yeun, E.J.; Shin-Park, K.K. Verification of the profile of mood states-brief: Cross-cultural analysis. *J. Clin. Psychol.* **2006**, *62*, 1173–1180. [CrossRef] [PubMed]
36. Osgood, C.E.; Suci, G.J.; Tannenbaum, P.H. *The Measurement of Meaning*; University of Illinois Press: Champaign, IL, USA, 1957.
37. Schiller, G.E. A comparison of measured and predicted comfort in office buildings. *ASHRAE Trans.* **1990**, *96*, 609–622.
38. Kim, S.J.; Lee, Y.S.; Park, H.I.; Joung, D.; Park, B.J. The Study on the Thermal Comfort in Urban Parks and Forests. *J. Korean Inst. For. Recreat.* **2019**, *23*, 41–52. (In Korean, with English abstract).
39. Song, C.; Ikei, H.; Kagawa, T.; Miyazaki, Y. Effects of walking in a forest on young women. *Int. J. Environ. Res. Public Health* **2019**, *16*, 229. [CrossRef]
40. Lee, J.; Tsunetsugu, Y.; Takayama, N.; Park, B.J.; Li, Q.; Song, C.; Komatsu, M.; Ikei, H.; Tyrväinen, L.; Kagawa, T.; et al. Influence of forest therapy on cardiovascular relaxation in young adults. *Evid. -Based Complement. Altern. Med.* **2014**, *2014*, 834360. [CrossRef] [PubMed]
41. Park, B.J.; Tsunetsugu, Y.; Kasetani, T.; Kagawa, T.; Miyazaki, Y. The physiological effects of Shinrin-yoku (taking in the forest atmosphere or forest bathing): Evidence from field experiments in 24 forests across Japan. *Environ. Health Prev. Med.* **2010**, *15*, 18–26. [CrossRef] [PubMed]
42. Takayama, N.; Korpela, K.; Lee, J.; Morikawa, T.; Tsunetsugu, Y.; Park, B.J.; Li, Q.; Tyrväinen, L.; Miyazaki, Y.; Kagawa, T. Emotional, restorative and vitalizing effects of forest and urban environments at four sites in Japan. *Int. J. Environ. Res. Public Health* **2014**, *11*, 7207–7230. [CrossRef]
43. Song, C.; Ikei, H.; Park, B.J.; Lee, J.; Kagawa, T.; Miyazaki, Y. Psychological benefits of walking through forest areas. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2804. [CrossRef]
44. Kobayashi, H.; Ikei, H.; Song, C.; Kagawa, T.; Miyazaki, Y. Comparing the impact of forest walking and forest viewing on psychological states. *Urban For. Urban Green.* **2021**, *57*, 126920. [CrossRef]
45. Schipperijn, J.; Ekholm, O.; Stigsdotter, U.K.; Toftager, M.; Bentsen, P.; Kamper-Jørgensen, F.; Randrup, T.B. Factors influencing the use of green space: Results from a Danish national representative survey. *Landsc. Urban Plan.* **2010**, *95*, 130–137. [CrossRef]