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An Investigation of Indoor Environment Quality on Occupants' Thermal Responses, Health, and Productivity: A Study Based on Physiological Data in Occupied Office Space

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Abstract: This study explores the impact of Indoor Environment Quality (IEQ) on the health and productivity of office workers in an office building in Fujisawa, Kanagawa, Japan. Previous studies have shown that IEQ can affect the physiological responses of occupants, such as of skin temperature, heart rate, and metabolic rate, which are indicators of health and productivity. However, most studies took place in controlled laboratory environments, which may not accurately represent real-life experiences. The study collected subjective and objective data from actual occupied office space, including on perceptions of IEQ, health, and productivity, and measurements of IEQ parameters such as on the thermal environment, light environment, indoor air quality, and acoustics. The study used correlation and linear regression methods to examine the relationship between IEQ, physiological data, and subjective responses to health and productivity. The stable thermal environment and low physical intensity of office work may contribute to the weak correlation between physiological data, thermal responses, and health–productivity variables. The results of this study can provide insights into how IEQ affects the psychological responses, well-being, and performance of office workers in real-world settings.

Keywords: IEQ; physiological data; health; productivity; occupied office building

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1. Introduction

The indoor environment quality (IEQ) is a critical factor in determining the health, comfort, and productivity of building occupants. Low IEQ dramatically lowers well-being and productivity at work [1]. This all-encompassing construct includes many characteristics related to thermal comfort, indoor air quality, lighting, and acoustics [2,3], with thermal comfort having the most impact on the occupants' comfort and productivity [4]. Recent trends show growing interest in using physiological measurements to continuously monitor IEQ and its impacts on building occupants. According to Persiani et al., the physical IEQ factors of the indoor environment are mostly related to biophysical elements such as the skin, brain, heart, and chemical signals [5]. Previous studies have also utilized the latest advancements in sensor technology to collect biometric information such as skin temperature and heart rate. Employing more rapid and objective examinations could be a very accurate way to examine how different stimuli affect people's bodies. According to Mansi et al., wearable technology could capture various bio-signals such as the skin temperature, heart rate, pulse rate, and metabolic rate of users during their active hours [6]. Thermal sensors in human skin control body temperature, which affects comfort level and the perception of heat [7]. Through the integration of physiological data from building occupants, studies using wearable devices, such as smartwatches and smart bracelets, have showed the potential in evaluating thermal comfort [8,9].

1.1. Skin Temperature Monitoring for Occupant Thermal Comfort, Well-Being, and Productivity

Skin temperature has become a useful indicator for tracking the productivity, well-being, and thermal comfort of building inhabitants. Numerous investigations have examined the connection between skin temperature and other facets of indoor environment occupant experiences. The correlation between skin temperature and respondents' subjective responses varied depending on which body segment was measured [10–14]. Previous research found that the subject's wrist temperature had a stronger association and was more responsive to changes in body temperature [10,12,13]. Morresi et al. discovered a relationship between the occupants' sense of heat and the skin temperature at the forehead, which is comparable to a previous study by Choi and Yeom [11]. Another study found that skin temperature at the ankle is more predictive than that measured at the wrist [14].

Certain changes in the thermal environment may cause the skin's temperature to shift. According to Cen et al., skin temperatures increase when the thermal sensation (TSV) changes from a cool state to a warm state [15]. The human body appears to be more resistant to cold than heat, as evidenced by Huizenga et al.'s observation that skin temperature responses are more sensitive to local chilling than local warming [16]. However, there was also a study that found that the relationship between skin temperature and thermal sensation in an unsteady thermal environment is still unclear, highlighting the need for further research [17].

Although skin temperature monitoring can offer significant insights on the thermal comfort, well-being, and productivity of occupants, it should be acknowledged that it has certain limits. The complex thermoregulatory system integrates multiple physiological signals, including as metabolic rate, skin temperature, and environmental cues (Liu et al., 2015; Corrigan et al., 2021) [18,19]. Skin temperature is just one part of this system. A person's thermal condition and comfort level may not be fully represented if skin temperature is the only factor considered. Various characteristics, such as age, gender, and level of acclimatization, contribute to the variation in how individuals perceive thermal comfort [19–21]. Multiple factors impact skin temperature, including individual attributes and environmental factors such as clothing and physical exertion [19,21,22]. Changes in environmental conditions may not be immediately reflected in skin temperature, leading to potential discrepancies between skin temperature and perceived thermal comfort.

1.2. Heart Rate Variability (HRV) and Occupant Thermal Comfort, Well-Being, and Productivity

Heart Rate Variability (HRV) has become more important as a measure for assessing the well-being and productivity of individuals in indoor situations. HRV, or heart rate variability, is a physiological phenomenon that measures the differences in time between consecutive heartbeats, often known as RR intervals. HRV is associated with the functioning of both the parasympathetic nervous system (PNS) and the sympathetic nervous system (SNS). The parasympathetic neural system (PNS) is known for its capacity to decrease heart rate and improve heart rate variability, whereas the sympathetic nervous system (SNS) possesses the opposite effect, increasing heart rate and decreasing heart rate variability. Therefore, while we are in a condition of rest and complete recovery, the heart rate is at its minimum level and the heart rate variability (HRV) is at its maximum level [23]. Both sympathetic and parasympathetic activities affect the Low Frequency (LF) component of heart rate variability, which generally ranges from 0.04 to 0.15 Hz; nonetheless, it is frequently linked to sympathetic activity, especially during stress or physical exertion. The High Frequency (HF) component, ranging from 0.15 to 0.40 Hz, primarily reflects parasympathetic (vagal) activity and is associated with relaxation and respiratory cycles. The LF/HFF ratio, representing the relationship between LF and HF power, serves as an indicator of sympathovagal balance, with higher values suggesting sympathetic dominance and lower values indicating parasympathetic dominance [24,25].

Several studies have confirmed the strong correlation between heart rate variability (HRV) and the subjective response to thermal comfort. When exposed to an uncomfortable temperature environment, the subject's LF/HF ratio increases, indicating increased activity of the sympathetic nervous system and a feeling of discomfort, as suggested by studies conducted by [26–28]. In a warm environment, the subjects' LF/HF ratio was found to be twice as high as that in a neutral or slightly cool environment. Also, studies have shown that several HRV indices, such as the mean RR, the RMSSD, the SDSD, the pNN25, and the sample entropy, can accurately predict a person's temperature [29]. In addition to thermal comfort, studies have linked HRV to occupational stress and overall well-being. Occupational stress can be associated with lower HRV, which indicates reduced parasympathetic activation [30]. Previous studies have demonstrated the use of HRV to analyze the physiological stress of students during sports competitions and school exams and have also found a correlation between the LF/HF index and thermal comfort during the recovery period [31,32].

1.3. Metabolic Rate of Office Workers

Bio-signal data can be utilized to approximate the metabolic rate of individuals in a building, taking into account their activities, age, and gender. Hasan et al. conducted a study utilizing Fitbit® wearable devices to examine the metabolic rates of individuals working in office settings. A study revealed that those who are not adequately slept exhibit elevated metabolic rates and may encounter pain throughout regular working hours. There was also a significant difference between the predicted metabolic rate (PMV) and measured metabolic rates. Metabolic rates can vary, not just between occupants performing similar daily tasks [33]. A different investigation conducted in Croatia on office buildings revealed that the observed metabolic rates often fell within the range of 1.0 to 2.0 MET, which is slightly higher than what is standard for office activities. These findings indicate that the use of static MET values in PMV calculations may be unsuitable [8]. In a study conducted in Japan by Nomoto et al., it was discovered that the average metabolic rates for office work were notably lower than the standard norms set by ISO and ASHRAE standards. The utilization of the measured metabolic rates led to a discrepancy of 0.8 °C to 1.9 °C in the computed thermally neutral temperature when compared to standard values [34].

In summary, the previous research suggests that bio-signals are a reliable method for assessing the physical and mental condition of persons in indoor settings, particularly with thermal comfort and other factors that impact indoor environmental quality (IEQ). By monitoring bio-signals, researchers and building managers can gather useful data on the physiological responses of occupants and make necessary modifications to the indoor environment. However, there are also conflicting results regarding the relationship between physiological data and the occupants' subjective responses to IEQ and productivity. Furthermore, the previous studies were mainly conducted in the experiment chambers or laboratory settings, which lack the complexities and variabilities of an actual office environment, leaving a critical gap in understanding how bio-signal relates to IEQ, productivity, and the well-being of occupants.

This study addresses this gap by investigating the correlation between IEQ and occupants' productivity and well-being in a real office environment, focusing specifically on the thermal environment, physiological data, and subjective responses. By conducting research in a real office setting, this study captures the actual variability of IEQ conditions that office occupants experience, offering insights that laboratory-based studies cannot provide. The novelty of this research lies in its validation of physiological data as predictors of health and productivity in daily office settings, providing an evidence-based foundation for future IEQ improvements in real-office environments. This study is limited to a single office building, with constraints on sample size and gender diversity due to voluntary participation. Furthermore, subjective responses may be influenced by participants' workload demands, impacting response comprehensiveness.

2. Materials and Methods

2.1. Measuring Equipment

We conducted measurements of indoor environment quality, user physiological parameters, and subjective response in a co-working space of an office building in Fujisawa, Kanagawa Prefecture (Japan), with a humid subtropical climate (Köppen Cfa). We conducted the measurements in the spring, summer, autumn, and winter, each lasting 30 days. The co-working space temperature was set based on the season (Table 1). The co-working space has an open layout type with air-conditioned space, located on the first floor, with the glass façades facing the northwest direction. The HVAC system has individual smart diffusers that are distributed evenly in every sitting area.

TR-74ui devices were used to collect the indoor air temperature and relative humidity, and illuminance data TR-52i devices collected the dry bulb temperature data. A Testo 405i Smart Probe device was used to collect the air velocity data. The data were collected from 9 measurement points. The sensors for collecting thermal environment data were set at a height of 110 cm from the floor surface (Figure 1). Smartwatches or commercial wristbands are the most suitable and convenient to use by subjects during the experiments. The Silmee–W22 collected the following data: number of steps, sleeping state, activity type, body movement during sleep, exercise intensity, skin temperature, pulse, UV dose, amount of conversation, acceleration data, and PPI (pulse wave peak interval) data. Exercise intensity data represent the energy expenditure data during activities. Based on the manual, the energy expenditure data are used to estimate the value of METs by dividing the value by 2. The calculation's MET value refers to the code published by the Ministry of Health, Labor, and Welfare of Japan (Physical Activity METs Chart). The device's default interval was set to 1 min for each parameter. The data from wearable devices were collected every 2 weeks. Kubios HRV Scientific 4.1.0 software (https://www.kubios.com/, accessed on 10 October 2024) was used to analyze the subjects' heart rate variability and stress index based on the heart rate data. PMV analysis was conducted using CBE Thermal Comfort Tools [35].

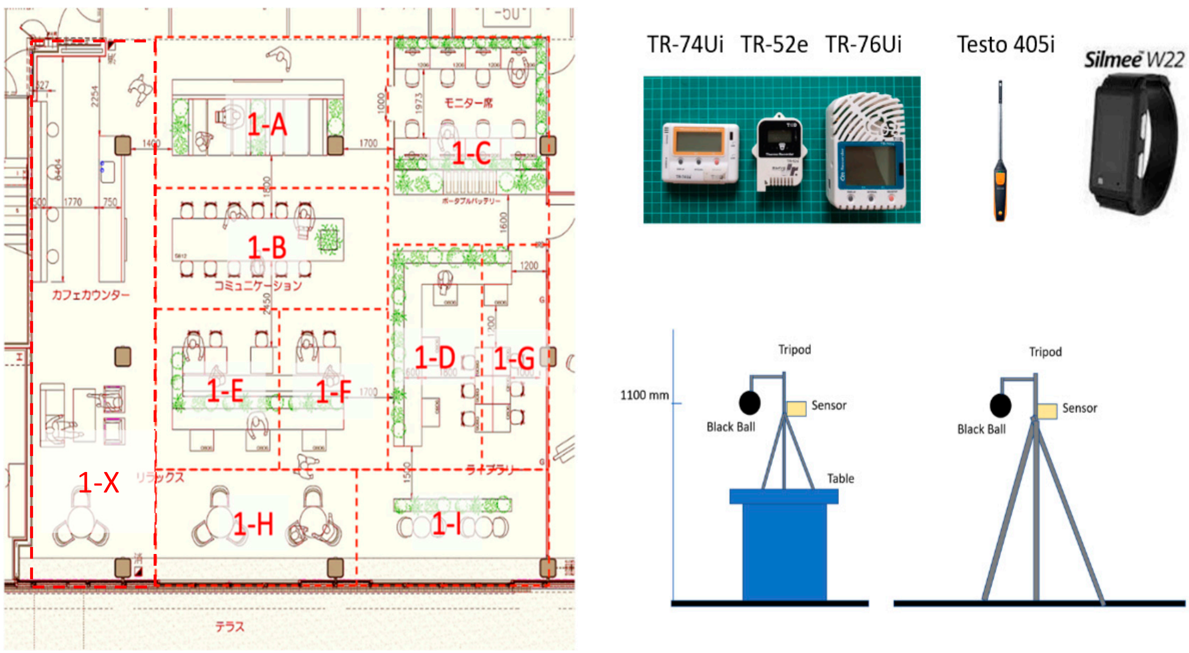


Figure 1. The co-working space plan and measurement devices. The measurement devices were installed at 9 measurement points (1-A to 1-I). These points also represent the seat location of the subjects.

Table 1. The measurements schedule.

Time	Time	MRT	HVAC Setting	Subjects	Valid Responses
Spring	February–March, 2023	12 °C	22 °C	9	47
Summer	June–July, 2023	30 °C	24 °C	9	44
Autumn	October–November, 2023	22 °C	24 °C	7	43
Winter	January–February, 2024	10 °C	21–23 °C	5	39

2.2. Survey

The questionnaire survey gathered the subjects' subjective responses. The participants had to answer the questionnaire according to how they felt about the performance of the IEQ in the co-working space. The participants wore wearable devices on the wrist to collect physiological data on energy expenditure, motion, skin temperature, and heart rate. The questionnaire [Appendix A] consisted of four sets of questions. The first set of questions concerned personal data (age, gender, time of stay, and type of work). The second set explored the occupants' responses to the thermal environment (thermal sensation vote, thermal comfort vote, thermal acceptance, humidity, air velocity, and thermal preference). The third set examined the occupants' responses to other IEQ parameters such as light, air quality, and acoustic performance. The fourth set investigated the relationship between IEQ and occupants' health and productivity. The questions regarding health and productivity were self-assessments of work progress, focus (concentration) level, relaxation level, stress level, fatigue level, and symptoms related to thermal and non-thermal conditions.

In the thermal sensation survey, we used the ASHRAE-PMV scale: neutral (0), slightly warm (1), warm (2), hot (3), cold (−3), cool (−2), and slightly cool (−1). A 5-point Likert scale with the following options—uncomfortable (−2), slightly uncomfortable (−1), neutral (0), slightly comfortable (1), and comfortable (2)—was utilized for the thermal comfort survey. The stress and fatigue parameters use a value range of 0 to 10, where the smallest value represents the best condition when the subject does not feel any stress or fatigue. Meanwhile, the highest value describes a condition where the level of stress and fatigue is maximum. For productivity parameters such as work progress, concentration, and relaxation, a value of 0 represents the lowest performance, while a value of 10 represents the best performance perceived by the subject. This study has collected data from 11 participants who voluntarily wore the wearable device during their routine office work. We anonymized the data to address privacy concerns. Subjects were required to fill out the questionnaire based on their experience during their stay in the co-working space. The subjects filled out the survey every time they changed their seat location. The minimum duration was 1 h in each seat location. Cronbach's Alpha was used to validate the questionnaires, with a high internal consistency showed by a Cronbach's Alpha of 0.7 or above.

This study uses linear regression and Spearman correlation analysis to investigate the relationship between variables. While Spearman correlation is a non-parametric method that may be more suitable for smaller datasets, linear regression shows a predictive relationship between variables. A p-value below 0.05 indicates a significant relationship. The R-squared value indicates the strength of the relationship. An R-squared value below 0.3 indicates a weak relationship. An R-squared value ranging from 0.3 to 0.6 indicates a moderate relationship. An R-squared value above 0.6 is considered a strong relationship [36]. Spearman's rank coefficient takes values from −1 to +1, where a value of −1 to −0.7 means a very strong negative correlation, a value of −0.7 to −0.5 means a strong negative correlation, a value of −0.5 to −0.3 means a moderate negative correlation, a value of −0.3 to −0.1 means a weak negative correlation, a value of 0.1 to + 0.3 means a weak positive correlation, a value of +0.3 to +0.5 means a moderate positive correlation, a value of +0.5 to +0.7 means a strong positive correlation, and a value of +0.7 to +1 means a very strong positive correlation.

3. Results

Eleven subjects submitted subjective responses on IEQ, health, and productivity. The IEQ measurement collected the indoor air temperature, relative humidity, illuminance, air velocity, and CO_2 concentration. The subjective responses were categorized into four groups, which are thermal perception, productivity, health, and symptoms. Thermal and non-thermal symptoms do not correlate strongly with most other variables, indicating distinct dimensions that may not align with the thermal responses, productivity, and health groups. Table 2 shows that Cronbach's Alpha analysis results in internal consistency across all groups (>0.7) except for the symptoms group (<0.7).

Table 2. Cronbach's Alpha analysis.

Group	Thermal Responses	Productivity	Health	Symptoms
Cronbach's Alpha	0.837	0.89	0.864	0.256

3.1. Indoor Environment Quality Data

The study collected high-quality data on indoor air temperature, relative humidity, and globe temperature (n = 20,256). Table 3 shows the indoor air temperature in the co-working space during office hours (8 a.m. to 9 p.m.). The indoor air temperature ranged from 18.4 °C to 25 °C in spring, 22.1 °C to 26.9 °C in summer, 20.4 °C to 25.8 °C in autumn, and 17.6 °C to 24.1 °C in winter. The mean temperatures were 21.6 °C in spring, 23.9 °C in summer, 23.6 °C in autumn, and 21.8 °C in winter. The relative humidity ranged from 34% to 70% in spring, 58% to 87% in summer, 28% to 78% in autumn, and 21% to 55% in winter. The mean relative humidity was 46% in spring, 69% in summer, 47% in autumn, and 39% in winter. We used the PMV analysis to predict the state of thermal sensation in the co-working space. The PMV ranged from −1.32 to −0.30 in spring, −0.97 to 0.82 in summer, −1.43 to 0.40 in autumn, and −1.64 to 0.23 in winter. The mean PMV was −0.43 in spring, −0.32 in summer, −0.32 in autumn, and −0.41 in winter.

Table 3. Thermal environment data.

Measurement	Indoor Temperature (°C)	Relative Humidity (%)	PMV
Spring	18.4–25 °C, mean 21.6 °C	34–70%, mean 46%	−1.32 to −0.30, mean −0.43 (Clo 1)
Summer	22.1–26.9 °C, mean 23.9 °C	58–87%, mean 69%	−0.97 to 0.82, mean −0.30 (Clo 0.62)
Autumn	20.4–25.8 °C, mean 23.6 °C	28–78%, mean 47%	−1.43 to 0.40, mean −0.32 (Clo 0.74)
Winter	17.6–24.1 °C, mean 21.8 °C	21–55%, mean 39%	−1.64 to 0.23, mean −0.41 (Clo 1)

Figure 2 shows the condition of indoor temperature, relative humidity, and PMV during office hours. The indoor temperature is relatively stable across seasons, with slight increases in summer and autumn. Summer has the highest median temperature (Figure 2a). Relative humidity shows significant seasonal variation, with the highest values in summer and the lowest in winter (Figure 2b). Spring and autumn have modern levels of relative humidity. PMV values are relatively stable but show slight seasonal variation. Most of the time, the PMVs were in a neutral state. Winter has the lowest PMV, indicating cooler thermal conditions (Figure 2c).

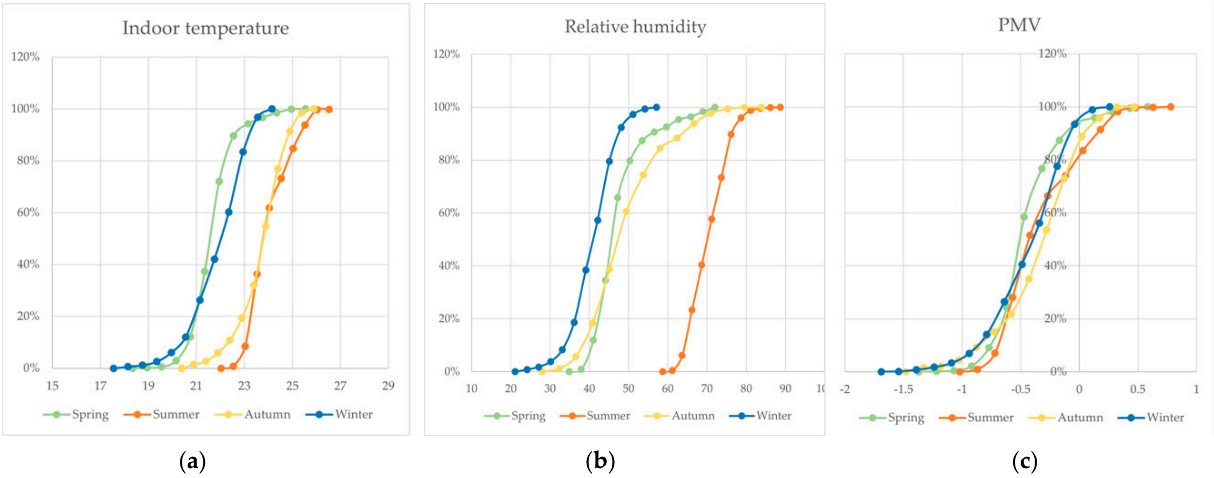


Figure 2. (**a**) Indoor temperature, (**b**) Relative humidity, and (**c**) PMV during office hours (8 a.m.–9 p.m.).

3.2. Physiological Data and Subjective Response

3.2.1. Skin Temperature, Heart Rate, and LF/HF

Figure 3 shows the data of skin temperature, heart rate, and LF/HF ratio based on the season. Summer exhibits the greatest average skin temperature in comparison to other seasons, which may be associated with an increased indoor temperature that leads to a rise in skin temperature. In winter, the skin temperature had the lowest mean value. The skin temperatures exhibited a wider range throughout fall and spring, suggesting a greater degree of variability during these transitional seasons. Winter showed slightly higher heart rates on average (68 bpm), followed by summer (67 bpm) and spring (67 bpm). Autumn has the lowest average heart rate (66 bpm). LF/HF has the widest range and highest values in spring, suggesting that individuals experience the most significant fluctuations in autonomic balance during this season. Autumn and summer show more tightly clustered data, indicating less variability in autonomic response compared to other seasons. Winter has less range than spring, indicating varied autonomic responses among subjects. Spring shows a higher tendency toward sympathetic activity (as indicated by the higher mean LF/HF ratio).

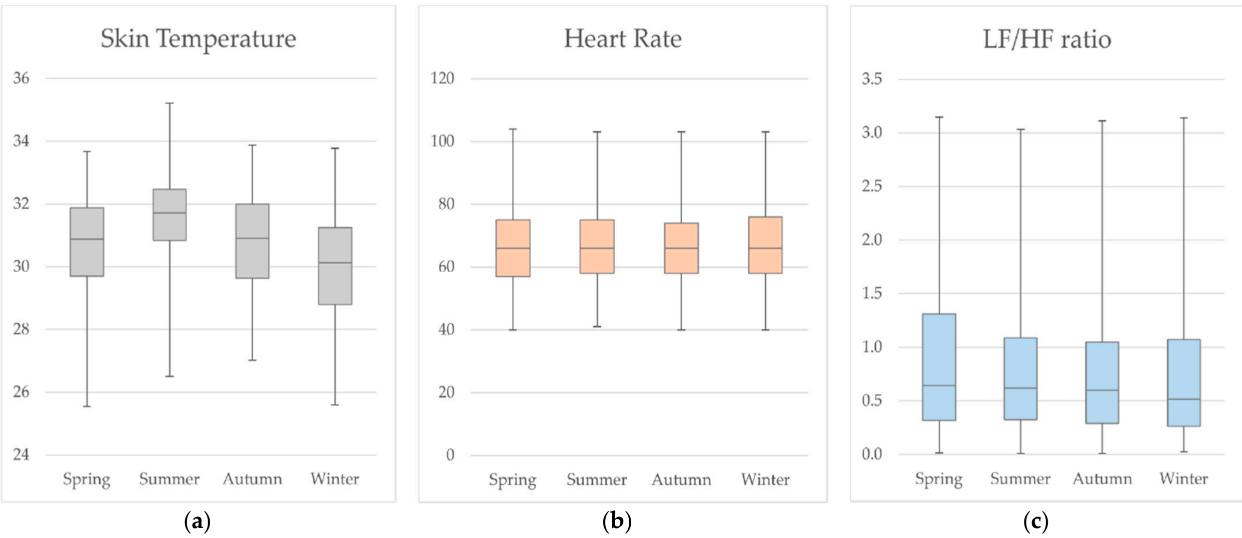


Figure 3. Physiological data based on the season. (**a**) The mean skin temperature in summer was higher. (**b**) Mean heart rates showed no significant difference across the season. (**c**) Winter has a lower LF/HF ratio.

3.2.2. Thermal Subjective Responses

Figure 4 shows the subjective responses to the thermal environment and thermal symptoms. Spring and summer have a broader distribution, with thermal sensation ranging from slightly cool to slightly warm. The medians were approximately neutral or slightly cool. The distribution in autumn and winter shows a greater trend towards a cooler sensation. Summer and autumn exhibit higher levels of comfort, with the majority of participants reporting a slight level of comfort, while a small number reported discomfort. Spring and winter have a wider range of comfort levels. Spring has a higher frequency of discomfort responses.

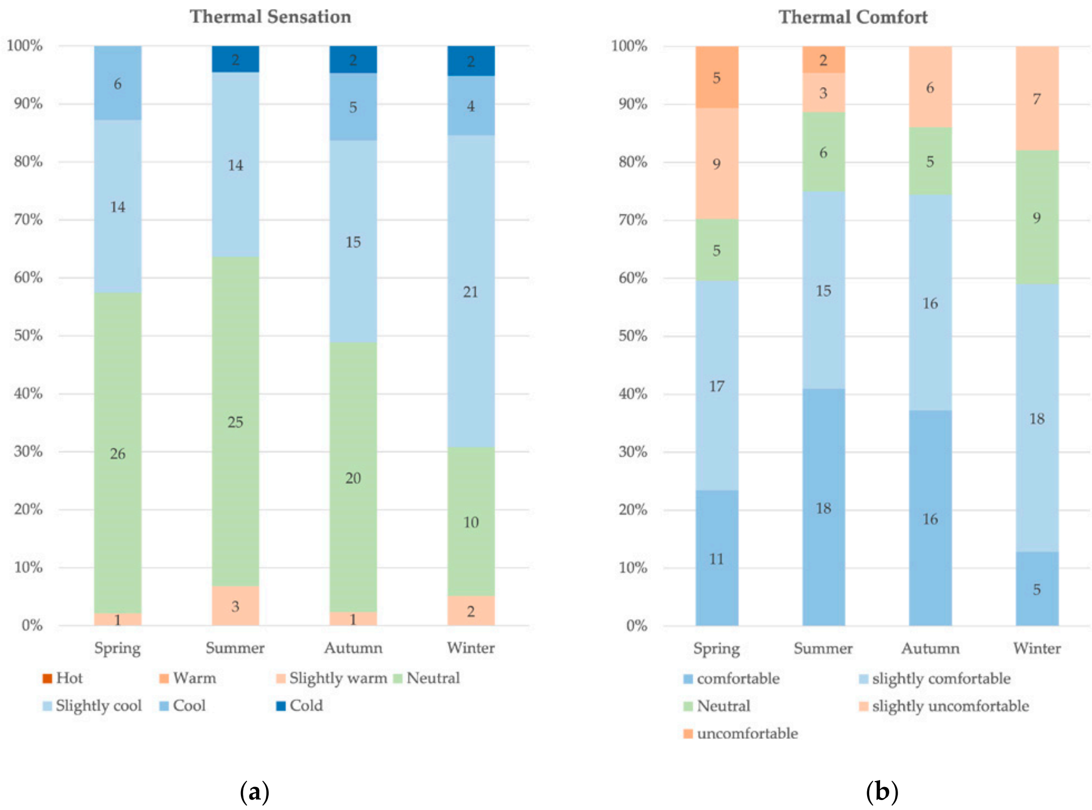
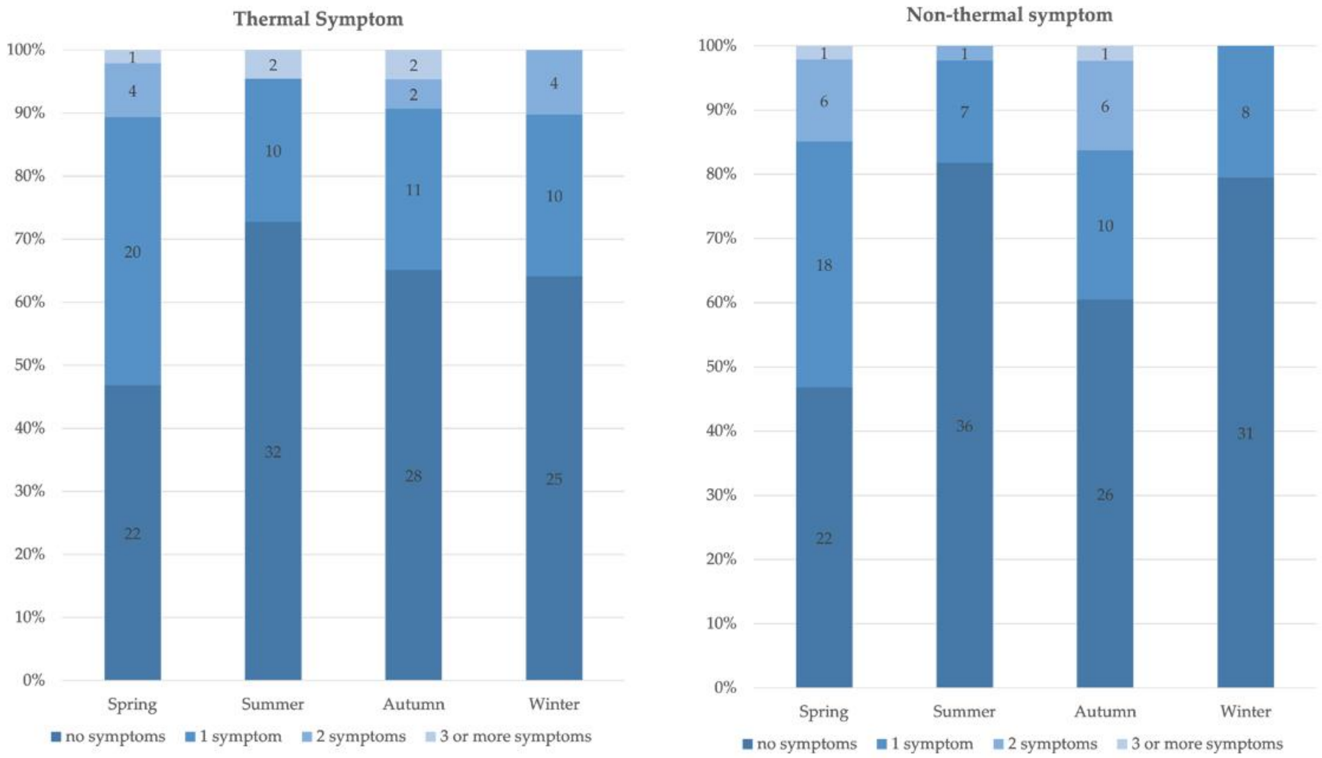


Figure 4. (**a**) Number of subjects who felt slightly cooler increased in winter. (**b**) Summer and autumn had more subjects who felt comfortable.

Figure 5 shows the reported thermal and non-hermal symptoms based on the season. Summer reportedly has the highest percentage of subjects who did not experience thermal symptoms. On the other hand, spring has the highest percentage of subjects who experienced thermal symptoms such as cool hands, cool feet, and chills on the upper and lower body. For the non-thermal symptoms, summer also has fewer subjects who experienced symptoms.

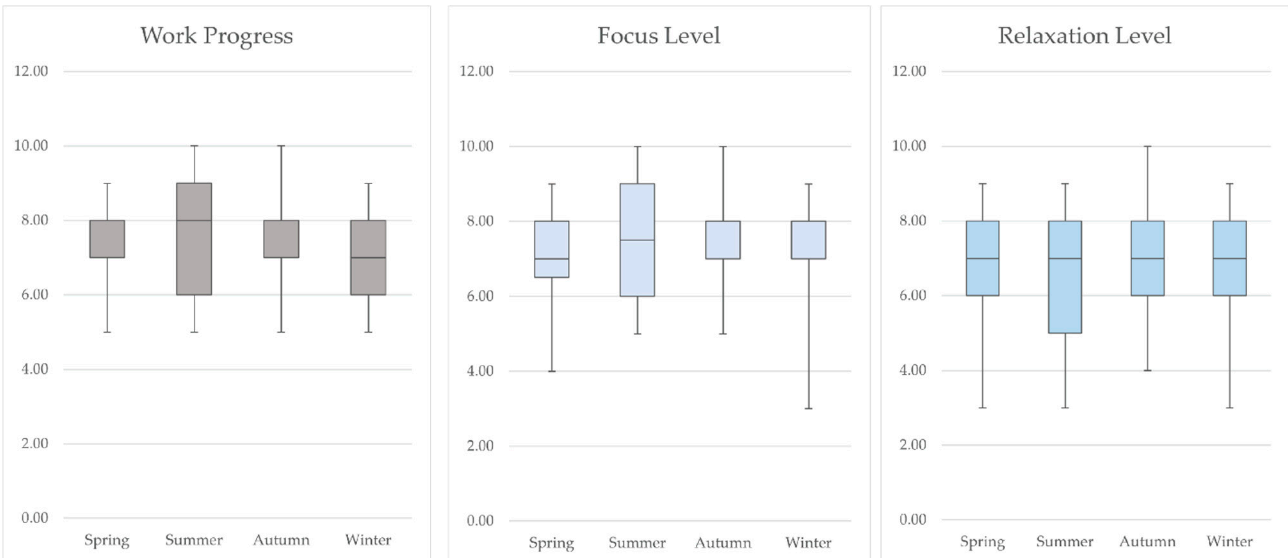
3.2.3. Health and Productivity

Figure 6 shows the seasonal data distribution of work progress, focus, and relaxation levels. The work progress is consistently high throughout all seasons, with Autumn exhibiting somewhat higher median values. The average work progress score varied between 7.31 and 7.67 between seasons, with autumn having the highest score. The season-to-season variability is minimal, suggesting consistent and uninterrupted progress in the task. The levels of focus remain rather stable across the seasons, with Autumn having the highest median and mean score for focus level. The average score of focus level varied between 7.28 and 7.56 among seasons. The interquartile ranges exhibit similarity, indicating a constant concentration throughout all areas. The relaxation levels are consistently high, with winter displaying a slightly higher average relaxation level score compared to other seasons. The mean score for relaxation ranged from 6.8 to 7.1, with the highest score being in autumn. Spring and summer have a wider range of data, indicating more variability in relaxation during these seasons.



(**a**) (**b**)

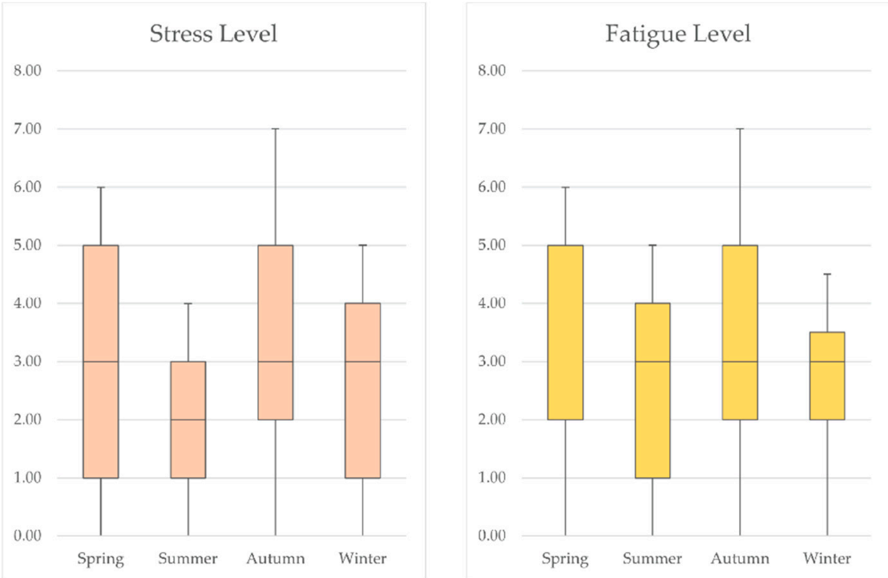
Figure 5. (**a**) Spring has the highest number of subjects who experienced thermal symptoms. (**b**) Spring has more subjects who experienced non-thermal symptoms.



(**a**) Work progress (**b**) Focus level (**c**) Relaxation level

Figure 6. Autumn has the highest mean score in work progress, focus level, and relaxation level.

Figure 7 shows the stress and fatigue levels based on season. Summer has the lowest mean stress level of 2.6 compared to other seasons, indicating generally lower stress levels of the subjects. Autumn contributed the highest mean stress level, with a broader range of values indicating higher variability in stress. Similar to the stress level, summer has the lowest mean fatigue score, and autumn has the highest mean score. The mean fatigue score ranged from 2.9 to 3.8.



(**a**) Stress level (**b**) Fatigue level

Figure 7. Seasonal data on stress and fatigue levels shows that the lowest stress and fatigue was in summer.

3.3. Relationship Between Physiological Data, Thermal Responses, and Indoor Thermal Environment

Table 4 shows the result of linear regression and Spearman correlation on physiological data and thermal environment variables. Linear regression shows that skin temperature has a weak but statistically significant relationship with indoor temperature, relative humidity, and PMV in the spring, autumn, winter, and across all seasons. The R-squared values show that skin temperature can explain about 11% (spring), 13% (autumn), 28% (winter), and 12% (all seasons) of the variance in ambient temperature. In summer, there is no correlation between skin temperature and indoor temperature, according to the regression analysis (p-value > 0.05). Still, on the contrary, the Spearman correlation shows a weak significant correlation ($\rho = 0.05$, $p < 0.05$) for summer data. Over all seasons, skin temperature has a stronger correlation with temperature rather than with relative humidity and PMV.

Linear regression and Spearman correlation show that heart rate has no significant relationship with indoor temperature, relative humidity, and PMV in each season and across all seasons (p-value > 0.05), except in autumn where the heart rate variable has a weak relationship with PMV (p-value < 0.05), based on linear regression for autumn, and the Spearman correlation shows an insignificant result. In each season, linear regression and correlation analysis indicate that the relationship between temperature and LF/HF was not significant. The p-value indicates a significant correlation between indoor temperature and the LF/HF ratio, as determined by the linear regression and correlation analysis conducted across all seasons. The R-square score, however, shows a relationship that is quite weak. No significant correlation or relationship was found between LF/HF, relative humidity, and PMV in any season and across all seasons, except for the correlation between PMV and LF/HF ratio in winter. This suggests that the LF/HF ratio, which reflects the equilibrium between the sympathetic and parasympathetic branches of the autonomic nervous system, may not be greatly influenced by factors associated with the stable thermal environment.

Table 4. Linear regression and correlation results on thermal environment and physiological data.

Skin Temperature		Temperature				RH				PMV			
		Linear Regression		Spearman		Linear Regression		Spearman		Linear Regression		Spearman	
Season	n	R^2	*p*-Value	ρ	*p*	R^2	*p*-Value	ρ	*p*	R^2	*p*-Value	ρ	*p*
Spring	1721	0.11	0.00	0.34	0.00	0.04	0.00	0.35	0.00	0.11	0.00	0.20	0.00
Summer	603	0.00	1.00	0.05	0.00	0.00	0.39	0.12	0.00	0.00	0.37	0.14	0.00
Autumn	860	0.13	0.00	0.44	0.00	0.03	0.00	0.38	0.00	0.10	0.00	0.12	0.00
Winter	677	0.28	0.00	0.51	0.00	0.03	0.00	0.54	0.00	0.31	0.00	0.07	0.08
All seasons	3861	0.12	0.00	0.34	0.00	0.09	0.00	0.26	0.00	0.07	0.00	0.29	0.00
Heart Rate		**Temperature**				**RH**				**PMV**			
		Linear Regression		**Spearman**		**Linear Regression**		**Spearman**		**Linear Regression**		**Spearman**	
Season	**n**	R^2	*p*-Value	ρ	*p*	R^2	*p*-Value	ρ	*p*	R^2	*p*-Value	ρ	*p*
Spring	1721	0.00	0.77	0.03	0.26	0.00	0.04	0.02	0.32	0.00	0.52	0.02	0.32
Summer	603	0.00	0.52	0.00	0.96	0.00	0.37	0.06	0.16	0.00	0.36	0.06	0.16
Autumn	860	0.00	0.72	0.02	0.59	0.00	0.66	0.04	0.19	0.01	0.02	0.04	0.19
Winter	677	0.00	0.80	−0.02	0.68	0.00	0.84	0.01	0.88	0.00	0.84	0.01	0.88
All seasons	3861	0.00	0.96	0.00	0.78	0.00	0.28	0.00	0.93	0.00	0.17	0.00	0.93
LF/HF		**Temperature**				**RH**				**PMV**			
		Linear Regression		**Spearman**		**Linear Regression**		**Spearman**		**Linear Regression**		**Spearman**	
Season	**n**	R^2	*p*-Value	ρ	*p*	R^2	*p*-Value	ρ	*p*	R^2	*p*-Value	ρ	*p*
Spring	1041	0.00	0.52	−0.04	0.19	0.00	0.38	−0.03	0.31	0.00	0.45	0.02	0.45
Summer	322	0.00	0.60	−0.02	0.66	0.00	0.33	−0.05	0.40	0.00	0.92	−0.05	0.41
Autumn	578	0.00	0.99	0.03	0.50	0.00	0.39	0.02	0.61	0.00	0.85	−0.03	0.52
Winter	283	0.00	0.88	0.00	0.99	0.00	0.70	0.00	0.99	0.00	0.83	−0.13	0.03
All Seasons	2224	0.00	0.00	−0.06	0.00	0.00	0.09	−0.02	0.30	0.00	0.50	−0.01	0.74

3.4. Relationship Between Physiological Data and Thermal Responses

Table 5 exhibits the result of linear regression and the correlation between physiological data and thermal responses. Linear regression and Spearman correlation indicate a substantial association between skin temperature and thermal sensation throughout all seasons. Nevertheless, the R-squared and correlation coefficient values suggest that the connections are tenuous. In summer, the relationship exhibits the highest level of strength, as indicated by an R-squared value of 0.14 and ρ value of 0.46. The correlation between skin temperature and thermal comfort is less robust throughout all seasons. The seasonal study findings indicate that there is a significant relationship between skin temperature and thermal comfort throughout the winter season, as evidenced by the highest R-squared and ρ values. The regression and correlation study indicates that there is no statistically significant correlation between heart rate, thermal sensation, and thermal comfort throughout all seasons. Linear regression shows no significant relationship between the LF/HF ratio, thermal sensation, and thermal comfort throughout all seasons, similar to heart rate. Spearman correlation indicates different results, where the LF/HF ratio has a weak positive correlation to thermal sensation.

Table 6 shows the linear regression and correlation between the physiological variables and symptoms. The linear regression and correlation analysis revealed a statistically significant connection between skin temperature, thermal symptoms, and non-thermal symptoms across all seasons (p-value < 0.05). The correlation coefficient value indicates a weak negative correlation between skin temperature and thermal symptoms. The correlation between skin temperature and non-thermal symptoms exhibits a weak positive correlation. There is a weak significant correlation between heart rate and thermal symptoms for all seasons, despite the regression analysis finding the opposite result. The opposite results were also found in spring and winter. This could imply an increased heart rate, potentially indicating more physical activity rather than thermal discomfort. Both linear regression and correlation also found that heart rate does not significantly correlate to non-thermal symptoms. Across all seasons, linear regression and Spearman correlation found that the LF/HF ratio has a significantly weak correlation with non-thermal symptoms. Both analyses also found that the LF/HF ratio has no significant relationship with thermal symptoms. It may suggest that the dynamic of LF/HF cannot be a mark of thermal discomfort.

Table 5. The linear regression and correlation results for physiological data and thermal responses.

Skin Temperature		**TSV**				**TCV**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	$\mathbf{R^2}$	***p*-Value**	**ρ**	***p*-Value**	$\mathbf{R^2}$	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.10	0.03	0.37	0.01	0.02	0.39	0.08	0.58
Summer	44	0.14	0.01	0.46	0.00	0.01	0.54	0.04	0.80
Autumn	43	0.06	0.10	0.19	0.23	0.05	0.16	0.11	0.49
Winter	39	0.11	0.04	0.32	0.05	0.13	0.02	0.34	0.03
All seasons	173	0.13	0.00	0.36	0.00	0.05	0.00	0.17	0.03
Heart Rate		**TSV**				**TCV**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	$\mathbf{R^2}$	***p*-Value**	**ρ**	***p*-Value**	$\mathbf{R^2}$	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.00	0.96	0.03	0.82	0.00	0.94	−0.04	0.80
Summer	44	0.02	0.31	0.23	0.13	0.03	0.23	0.15	0.35
Autumn	43	0.00	0.76	−0.16	0.31	0.01	0.61	−0.20	0.21
Winter	39	0.01	0.48	0.09	0.58	0.03	0.31	0.18	0.27
All seasons	173	0.00	0.54	0.03	0.68	0.00	0.41	0.02	0.83
LF/HF		**TSV**				**TCV**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	$\mathbf{R^2}$	***p*-Value**	**ρ**	***p*-Value**	$\mathbf{R^2}$	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.00	0.80	0.01	0.92	0.00	0.87	0.04	0.80
Summer	44	0.01	0.47	0.17	0.28	0.00	0.95	−0.04	0.82
Autumn	43	0.03	0.25	0.24	0.12	0.07	0.09	0.26	0.09
Winter	39	0.01	0.51	0.04	0.80	0.01	0.56	0.03	0.86
All Seasons	173	0.02	0.09	0.19	0.01	0.01	0.13	0.12	0.12

3.5. Relationship Between Physiological Data, Health, and Productivity

Table 7 shows the linear regression and the correlation results exhibit a significant relationship between skin temperature and productivity variables in all seasons, but it is especially strong in summer. The correlation analysis indicates that increased skin temperatures may be associated with lower productivity. In the same vein, increased skin temperatures are linked to decreased occupant concentration levels, with the most significant correlation observed during the summer season (R-squared = 0.49, ρ = −0.71). A substantial relationship was observed between skin temperature and levels of relaxation, both during the summer and throughout the entire seasons. The correlation strengths were varied each season and summer shows the strongest correlation. This suggests that skin temperature is likely influenced by seasonal warmth.

Table 6. The linear regression and correlation results for physiological data and symptoms.

Skin Temperature		**Thermal Symptoms**				**Non-Thermal Symptoms**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	***p*-Value**	**ρ**	***p*-Value**	R^2	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.07	0.06	−0.26	0.07	0.10	0.03	0.27	0.07
Summer	44	0.06	0.10	−0.33	0.03	0.01	0.63	0.09	0.55
Autumn	43	0.07	0.08	−0.17	0.26	0.06	0.12	0.22	0.17
Winter	39	0.11	0.04	−0.31	0.05	0.08	0.09	0.27	0.10
All seasons	173	0.08	0.00	−0.26	0.00	0.03	0.02	0.17	0.02
Heart Rate		**Thermal Symptoms**				**Non-Thermal Symptoms**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	***p*-Value**	**ρ**	***p*-value**	R^2	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.03	0.24	−0.32	0.03	0.00	0.72	0.09	0.57
Summer	44	0.00	0.97	−0.11	0.47	0.00	0.90	−0.14	0.37
Autumn	43	0.00	0.88	0.03	0.85	0.00	0.82	0.00	0.98
Winter	39	0.09	0.07	−0.33	0.04	0.00	0.89	−0.03	0.86
All seasons	173	0.02	0.10	−0.20	0.01	0.02	0.10	−0.08	0.30
LF/HF		**Thermal Symptoms**				**Non-Thermal Symptoms**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	***p*-Value**	**ρ**	***p*-Value**	R^2	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.00	0.67	−0.02	0.91	0.07	0.07	0.43	0.00
Summer	44	0.01	0.57	0.00	0.99	0.00	0.67	0.03	0.83
Autumn	43	0.07	0.08	−0.27	0.08	0.00	0.83	0.10	0.52
Winter	39	0.00	0.70	−0.03	0.84	0.00	0.76	0.06	0.69
All Seasons	173	0.01	0.18	−0.03	0.71	0.03	0.01	0.30	0.00

Table 7. Linear regression and correlation result of physiological and productivity variables.

Skin Temperature		**Work Progress**				**Focus Level**				**Relaxation Level**			
		Regression		**Spearman**		**Regression**		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	***p*-Value**	**ρ**	***p*-Value**	R^2	***p*-Value**	**ρ**	***p*-Value**	R^2	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.02	0.36	−0.14	0.36	0.02	0.33	−0.17	0.25	0.10	0.03	−0.26	0.07
Summer	44	0.55	0.00	−0.74	0.00	0.49	0.00	−0.71	0.00	0.35	0.00	−0.59	0.00
Autumn	43	0.21	0.00	−0.47	0.00	0.13	0.02	−0.41	0.01	0.05	0.17	−0.32	0.04
Winter	39	0.00	0.90	−0.11	0.51	0.00	0.81	−0.16	0.34	0.00	0.69	−0.21	0.20
All	173	0.11	0.00	−0.33	0.00	0.08	0.00	−0.34	0.00	0.09	0.00	−0.35	0.00
Heart Rate		**Work Progress**				**Focus Level**				**Relaxation Level**			
		Regression		**Spearman**		**Regression**		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	***p*-Value**	**ρ**	***p*-Value**	R^2	***p*-Value**	**ρ**	***p*-Value**	R^2	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.09	0.04	−0.27	0.07	0.05	0.12	−0.24	0.10	0.06	0.11	−0.23	0.13
Summer	44	0.00	0.75	−0.10	0.53	0.00	0.69	−0.10	0.50	0.01	0.59	0.03	0.86
Autumn	43	0.11	0.03	−0.29	0.06	0.06	0.12	−0.16	0.31	0.06	0.10	−0.24	0.12
Winter	39	0.07	0.11	−0.34	0.04	0.01	0.47	−0.25	0.12	0.05	0.18	−0.33	0.04
All	173	0.05	0.00	−0.25	0.00	0.02	0.04	−0.19	0.01	0.01	0.11	−0.17	0.02
LF/HF		**Work Progress**				**Focus Level**				**Relaxation Level**			
		Regression		**Spearman**		**Regression**		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	***p*-Value**	**ρ**	***p*-Value**	R^2	***p*-Value**	**ρ**	***p*-Value**	R^2	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.04	0.16	−0.24	0.11	0.03	0.22	−0.24	0.10	0.03	0.25	−0.18	0.21
Summer	44	0.10	0.03	−0.13	0.41	0.09	0.05	−0.11	0.46	0.10	0.03	−0.28	0.07
Autumn	43	0.05	0.16	0.04	0.81	0.03	0.24	−0.06	0.70	0.03	0.27	0.04	0.78
Winter	39	0.03	0.27	−0.22	0.17	0.02	0.36	−0.18	0.27	0.06	0.12	−0.26	0.10
All	173	0.00	0.68	−0.06	0.44	0.00	0.50	−0.10	0.20	0.01	0.20	−0.17	0.03

The analysis revealed weak associations between heart rate and productivity variables across all seasons, except for relaxation levels, where the regression result shows an insignificant relationship with heart rate but correlation analysis indicates a weak negative correlation (Table 7). The R-squared and correlation coefficient values were often low, suggesting that heart rate has little predictive power for these psychological characteristics. Most of the p-values exceeded the threshold of 0.05, indicating insufficient statistical evidence to prove a meaningful relationship between the heart rate and relaxation level of the subjects. Similar results were found between the LF/HF ratio and productivity variables across all seasons.

Table 8 shows the linear regression and correlation analysis of physiological data and health variables. There is an obvious correlation between skin temperature, stress, and fatigue level, particularly in the summer and autumn seasons. The statistical data indicates that the relationships are significant, despite the R-squared and ρ values suggesting weak correlations across all seasons. In autumn, the associations between heart rate and stress level, as well as fatigue level, were statistically more apparent. The relationship between heart rate and stress level in autumn was shown to be statistically significant, as indicated by a p-value of less than 0.05 (Table 8). However, for the majority of other seasons and in general, the relationships did not exhibit any statistically significant outcomes. Both regression and correlation analysis found that the LF/HF ratio has no significant relationship or correlation with the stress and fatigue variables.

Table 8. Linear regression and correlation result of physiological and health variables.

Skin Temperature		**Stress Level**				**Fatigue Level**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	**R^2**	**p-Value**	**ρ**	**p-Value**	**R^2**	**p-Value**	**ρ**	**p-Value**
Spring	47	0.04	0.17	0.19	0.20	0.08	0.06	0.28	0.06
Summer	44	0.11	0.03	0.45	0.00	0.13	0.02	0.41	0.01
Autumn	43	0.14	0.01	0.51	0.00	0.18	0.00	0.44	0.00
Winter	39	0.00	0.93	0.06	0.72	0.00	0.81	0.06	0.73
All	173	0.04	0.01	0.27	0.00	0.06	0.00	0.29	0.00
Heart Rate		**Stress Level**				**Fatigue Level**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	**R^2**	**p-Value**	**ρ**	**p-Value**	**R^2**	**p-Value**	**ρ**	**p-Value**
Spring	47	0.00	0.75	0.09	0.56	0.00	0.93	0.01	0.93
Summer	44	0.03	0.28	−0.16	0.29	0.03	0.28	−0.15	0.32
Autumn	43	0.10	0.04	0.34	0.03	0.10	0.04	0.33	0.03
Winter	39	0.00	0.68	0.19	0.24	0.03	0.32	0.28	0.08
All	173	0.00	0.63	0.08	0.27	0.00	0.56	0.10	0.20
LF/HF		**Stress Level**				**Fatigue Level**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	**R^2**	**p-Value**	**ρ**	**p-Value**	**R^2**	**p-Value**	**ρ**	**p-Value**
Spring	47	0.00	0.81	0.00	0.99	0.00	0.76	0.11	0.44
Summer	44	0.01	0.44	0.11	0.49	0.03	0.28	0.28	0.06
Autumn	43	0.03	0.28	−0.02	0.89	0.04	0.21	−0.03	0.83
Winter	39	0.01	0.50	0.16	0.34	0.03	0.34	0.20	0.22
All	173	0.00	0.87	0.10	0.19	0.00	0.85	0.13	0.08

3.6. Relationship Between Thermal Environment, Thermal Responses, and Health–Productivity

Temperature reportedly has a significant correlation with thermal sensation in spring, autumn, winter, and all seasons, as seen in Table 9. However, the relationship was weak. In summer, there was no significant relationship between temperature and thermal sensation. Temperature has a weak, significant relationship with thermal comfort in autumn, winter, and across all seasons. The R-squared value shows temperature has a stronger relationship with thermal comfort than with thermal sensation. The analysis also found a weak, significant relationship between humidity, thermal sensation, and thermal comfort. Similar to temperature, relative humidity has a stronger relationship with thermal comfort than with thermal sensation, according to the R-squared value. In the spring and overall season, linear regression shows a weak, significant relationship between PMV and thermal sensation. PMV has a significant impact on thermal comfort in the spring, winter, and over all seasons. The R-squared value indicates that PMV has a stronger relationship to thermal comfort (TCV) than thermal sensation.

Table 9. Linear regression and correlation between thermal environment and thermal responses.

Temperature		**Thermal Sensation**				**Thermal Comfort**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	**R^2**	***p*-Value**	**ρ**	***p*-Value**	**R^2**	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.18	0.00	0.40	0.01	0.08	0.05	0.20	0.18
Summer	44	0.01	0.56	−0.07	0.64	0.00	0.76	−0.12	0.45
Autumn	43	0.24	0.00	0.43	0.00	0.35	0.00	0.52	0.00
Winter	39	0.23	0.00	0.38	0.02	0.17	0.01	0.36	0.03
All	173	0.10	0.00	0.29	0.00	0.15	0.00	0.37	0.00
Relative Humidity		**Thermal Sensation**				**Thermal Comfort**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	**R^2**	***p*-Value**	**ρ**	***p*-Value**	**R^2**	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.21	0.00	0.39	0.01	0.10	0.03	0.31	0.03
Summer	44	0.01	0.48	0.07	0.67	0.01	0.59	0.00	0.98
Autumn	43	0.11	0.03	0.23	0.14	0.16	0.01	0.21	0.18
Winter	39	0.17	0.01	0.26	0.11	0.15	0.01	0.44	0.01
All	173	0.07	0.00	0.30	0.00	0.05	0.00	0.24	0.00
PMV		**Thermal Sensation**				**Thermal Comfort**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	**R^2**	***p*-Value**	**ρ**	***p*-Value**	**R^2**	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.16	0.00	0.43	0.00	0.10	0.03	0.24	0.10
Summer	44	0.00	0.81	0.03	0.86	0.00	0.70	−0.13	0.39
Autumn	43	0.01	0.61	0.29	0.05	0.00	0.94	0.33	0.03
Winter	39	0.04	0.21	0.34	0.03	0.17	0.01	0.37	0.02
All	173	0.05	0.00	0.22	0.00	0.03	0.02	0.18	0.02

Table 10 shows the results of linear regression and the correlation between the thermal environment and productivity variables. Temperature has a minimal effect on work progress, with very low R-squared values and non-significant *p*-values, indicating that the thermal environment does not strongly influence work progress in these seasons. Across all seasons, the effect of temperature on focus level was negligible, with very low R-squared values and non-significant *p*-values, indicating that temperature does not significantly impact focus levels. The impact of temperature on the relaxation level was insignificant regardless of the season, as indicated by low R-squared values and a non-significant relationship (p-value < 0.05). Both analyses also found that relative humidity has no significant relationship with work progress, focus level, and relaxation level in each season and throughout all seasons.

Table 10. Linear regression results of thermal environment and productivity variables.

Temperature		**Work Progress**				**Focus Level**				**Relaxation Level**			
		Regression		**Spearman**		**Regression**		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	***p*-Value**	ρ	***p*-Value**	R^2	***p*-Value**	ρ	***p*-Value**	R^2	***p*-Value**	ρ	***p*-Value**
Spring	47	0.01	0.61	0.16	0.29	0.00	0.90	0.09	0.54	0.00	0.95	−0.05	0.74
Summer	44	0.00	0.96	−0.05	0.75	0.00	0.81	0.01	0.93	0.01	0.45	0.08	0.58
Autumn	43	0.07	0.10	−0.28	0.07	0.04	0.22	−0.21	0.18	0.02	0.31	0.02	0.89
Winter	39	0.00	0.77	−0.02	0.90	0.00	0.78	−0.08	0.65	0.01	0.63	−0.02	0.88
All Seasons	173	0.00	0.94	0.00	0.99	0.00	0.73	0.00	0.97	0.00	0.55	0.02	0.79
Relative Humidity		**Work progress**				**Focus Level**				**Relaxation Level**			
		Regression		**Spearman**		**Regression**		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	***p*-Value**	ρ	***p*-Value**	R^2	***p*-Value**	ρ	***p*-Value**	R^2	***p*-Value**	ρ	***p*-Value**
Spring	47	0.05	0.14	0.16	0.27	0.03	0.24	0.17	0.25	0.00	0.70	0.08	0.60
Summer	44	0.00	0.78	0.00	0.98	0.01	0.60	−0.03	0.86	0.00	0.87	0.05	0.77
Autumn	43	0.03	0.23	−0.11	0.48	0.01	0.62	0.06	0.72	0.00	1.00	0.11	0.47
Winter	39	0.01	0.52	−0.14	0.40	0.01	0.60	−0.11	0.49	0.01	0.57	−0.16	0.32
All Seasons	173	0.00	0.98	0.00	0.97	0.00	0.91	0.02	0.75	0.00	0.95	0.01	0.93
PMV		**Work progress**				**Focus Level**				**Relaxation Level**			
		Regression		**Spearman**		**Regression**		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	***p*-Value**	ρ	***p*-Value**	R^2	***p*-Value**	ρ	***p*-Value**	R^2	***p*-Value**	ρ	***p*-Value**
Spring	47	0.01	0.42	0.17	0.26	0.00	0.64	0.10	0.50	0.00	0.96	−0.05	0.72
Summer	44	0.00	0.77	−0.03	0.85	0.00	0.99	0.01	0.96	0.01	0.60	0.10	0.50
Autumn	43	0.09	0.05	−0.37	0.01	0.06	0.11	−0.28	0.07	0.02	0.42	0.02	0.88
Winter	39	0.00	0.71	0.00	0.99	0.00	0.76	−0.07	0.67	0.01	0.56	0.00	0.99
All Seasons	173	0.01	0.26	−0.07	0.35	0.00	0.44	−0.04	0.59	0.01	0.30	0.04	0.59

Across the seasons, the effect of PMV on work progress was generally weak and not statistically significant, with low R-squared values and *p*-values above 0.05 except in autumn. The relationship between PMV and work progress in autumn was determined to be statistically significant, with a *p*-value of less than 0.05. These findings show that higher PMV levels, which indicate warmer conditions, could result in a decline in productivity. Nevertheless, the R-squared values (0.09) indicate a poor correlation between the variables. The statistical analysis indicates that the impact of PMV on work progress, relaxation, and focus levels was not significant throughout all seasons. This is supported by the low R-squared values and *p*-values that are more than 0.05. This implies that PMV has an insignificant impact on levels of concentration (focus).

As shown in Table 11, the impact of temperature on stress and fatigue levels was generally minimal and lacked statistical significance in each season and across all seasons. A similar result was found in the relationship between relative humidity, stress, and fatigue levels. Throughout all seasons—spring, summer, autumn, and winter—there was a small positive correlation between PMV (predicted mean vote) stress and fatigue level. However, it is important to note that this relationship did not achieve statistical significance, both in linear regression and Spearman correlation. The findings suggest that temperature has little effect on both productivity and health variables, encompassing factors such as work progress, focus, relaxation, stress, and fatigue throughout the seasons. The low R-squared and ρ values suggest that temperature has a limited impact on these outcomes' variability. This suggests that other factors may have a greater influence on health and productivity variables.

Table 11. Linear regression results of thermal environment and health variables.

Temperature		**Stress Level**				**Fatigue Level**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	***p*-Value**	**ρ**	***p*-Value**	R^2	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.010	0.490	0.005	0.975	0.020	0.370	−0.077	0.607
Summer	44	0.030	0.300	0.107	0.489	0.050	0.130	0.135	0.382
Autumn	43	0.010	0.610	0.167	0.283	0.050	0.130	0.303	0.048
Winter	39	0.030	0.300	−0.109	0.509	0.000	0.990	−0.010	0.950
All Seasons	173	0.000	0.720	0.052	0.497	0.010	0.170	0.124	0.103
Relative Humidity		**Stress Level**				**Fatigue Level**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	***p*-Value**	**ρ**	***p*-Value**	R^2	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.010	0.410	−0.189	0.204	0.010	0.460	−0.060	0.689
Summer	44	0.000	0.960	0.041	0.790	0.010	0.540	0.046	0.765
Autumn	43	0.010	0.530	−0.004	0.979	0.020	0.340	0.111	0.480
Winter	39	0.000	0.780	0.086	0.604	0.020	0.380	0.182	0.267
All Seasons	173	0.010	0.240	−0.087	0.256	0.000	0.790	−0.012	0.872
PMV		**Stress Level**				**Fatigue Level**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	***p*-Value**	**ρ**	***p*-Value**	R^2	***p*-Value**	**ρ**	***p*-Value**
Spring	47	0.000	0.670	0.008	0.959	0.020	0.300	−0.037	0.804
Summer	44	0.050	0.140	0.203	0.187	0.070	0.070	0.207	0.178
Autumn	43	0.000	0.880	0.106	0.499	0.060	0.110	0.302	0.049
Winter	39	0.000	0.720	−0.063	0.703	0.000	0.960	−0.014	0.933
All Seasons	173	0.000	0.580	0.041	0.591	0.030	0.020	0.112	0.142

Table 12 shows the linear regression and correlation result for the thermal environment, thermal symptoms, and non-thermal symptoms. Both linear regression and Spearman correlation found that the temperature significantly correlates to thermal symptoms during the spring, autumn, winter, and over all seasons, indicating that higher temperatures were associated with decreased thermal symptoms. Nevertheless, the strength of the relationship of these variables was weak. The relationship between temperature and non-thermal symptoms was consistently weak and often failed to reach statistical significance, suggesting that temperature may not have a significant impact on the occurrence of these symptoms.

The effect of relative humidity (RH) on thermal symptoms was weak and insignificant across all seasons. The regression and correlation analysis also revealed an insignificant connection between relative humidity and non-thermal symptoms. PMV significantly correlated to thermal symptoms, especially in autumn and winter, with a higher PMV (warmer conditions) associated with fewer thermal symptoms. This relationship was weaker or non-significant in summer (p-value > 0.05). Similar to the findings with temperature, the relationship between PMV and non-thermal symptoms was generally weak and not statistically significant.

These findings exhibit the complex relationship between physiological responses and thermal environment parameters in a real office setting. Skin temperature correlates with thermal environment parameters, suggesting sensitivity to ambient conditions. However, personal attributes like age and gender may also contribute to skin temperature. Skin temperature may serve as a reliable indicator of subjective thermal perception, even with a slightly weaker association than in previous laboratory-based studies. Skin temperature may also be a predictor in detecting health and productivity in an office setting. Heart rate may be less sensitive to thermal environment change in office settings, especially in places that have stable thermal environments and low physical activity. This highlights the need for a comprehensive approach that includes both environmental parameters and personal attributes for accurate occupant comfort, productivity, and well-being prediction. The study emphasizes the need for further investigation into adaptive strategies for HVAC control, incorporating physiological responses as part of a more comprehensive approach to IEQ.

Table 12. Linear regression of thermal environment and symptoms.

Temperature		Thermal Symptoms				Non-Thermal Symptoms			
		Regression		Spearman		Regression		Spearman	
Season	n	R^2	p-Value	ρ	p-Value	R^2	p-Value	ρ	p-Value
Spring	47	0.09	0.04	−0.28	0.06	0.00	0.75	−0.05	0.72
Summer	44	0.00	0.98	0.05	0.73	0.03	0.30	−0.20	0.19
Autumn	43	0.32	0.00	−0.48	0.00	0.00	0.85	0.06	0.71
Winter	39	0.19	0.01	−0.38	0.02	0.00	0.76	0.00	1.00
All	173	0.12	0.00	−0.36	0.00	0.01	0.15	−0.12	0.11
Relative Humidity		**Thermal Symptoms**				**Non-Thermal Symptoms**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	p-Value	ρ	p-Value	R^2	p-Value	ρ	p-Value
Spring	47	0.03	0.24	−0.18	0.22	0.00	0.72	−0.04	0.80
Summer	44	0.00	0.97	0.05	0.76	0.00	0.90	0.05	0.73
Autumn	43	0.00	0.88	−0.09	0.57	0.00	0.82	0.21	0.17
Winter	39	0.09	0.07	−0.33	0.04	0.00	0.89	−0.02	0.92
All	173	0.02	0.10	−0.17	0.02	0.02	0.10	−0.05	0.49
PMV		**Thermal Symptoms**				**Non-Thermal Symptoms**			
		Regression		**Spearman**		**Regression**		**Spearman**	
Season	**n**	R^2	p-Value	ρ	p-Value	R^2	p-Value	ρ	p-Value
Spring	47	0.09	0.04	−0.24	0.10	0.01	0.61	0.02	0.92
Summer	44	0.00	0.81	0.13	0.41	0.02	0.33	−0.10	0.53
Autumn	43	0.23	0.00	−0.34	0.03	0.01	0.64	−0.04	0.80
Winter	39	0.21	0.00	−0.44	0.00	0.00	0.73	−0.04	0.82
All	173	0.10	0.00	−0.25	0.00	0.00	0.54	−0.05	0.55

4. Discussion

Linear regression shows that an increase in skin temperature is affected by an increase in the indoor temperature. The R-squared value indicates approximately 10.8% of the variation in skin temperature, indicating that although temperature may significantly affect skin temperature. However, there may be other factors such as age, gender, or personal attributes that also influence skin temperature. The results are consistent with the prior research conducted by Cen et al. [15], Huizenga et al. [16], and Moon et al. [37], which demonstrated a substantial correlation between ambient temperature and skin temperature. On the contrary, Čulić et al. found that at lower temperatures, there is no significant association between skin temperature and air temperature [8].

This study discovered a statistically significant correlation between skin temperature and thermal response variables such as thermal sensation and comfort. However, this relationship shows a slightly weaker correlation in comparison to previous research. Skin temperature may have a significant correlation with parameters linked to both health and productivity, despite the minimal impact of individual metrics. The regression analysis suggests that higher skin temperatures may be a sign of lower productivity. This finding aligns with the findings of Yeom and Delogu (2021), indicating that lower skin temperatures positively impact individuals' cognitive ability [10]. The stronger correlation of skin temperature with thermal sensation in an actual office setting might be caused by the more natural adaptation processes of the human body in response to varying environmental factors that are absent in controlled laboratory conditions.

The regression analysis indicates that there is no significant correlation between heart rate, indoor temperature, relative humidity, and PMV in any of the seasons, as indicated by a *p*-value greater than 0.05. However, heart rate has a weak relationship with thermal symptoms and productivity parameters. These findings are consistent with the studies conducted by Cen et al. and Čulić et al., which determined that fluctuations in heart rate do not have any meaningful impact on predicting thermal comfort in a cold-to-neutral thermal environment [8,15]. On the other hand, Wu et al. (2024) discovered that the heart rate variable is a reliable indicator to predict the thermal sensations and thermal comfort of subjects [38]. However, the heart rate's weak correlation with productivity parameters suggests that it may have a modest, indirect role, likely influenced by psychological or cognitive factors rather than physical thermal conditions.

The current study has found no significant correlation between the LF/HF ratio and thermal comfort and thermal symptoms, but it shows a weak correlation with thermal sensation and non-thermal symptoms. This conclusion contradicts prior research that has claimed a link between the LF/HF ratio and thermal comfort [13,39,40]. The LF/HF ratio also does not have a significant relationship with the productivity variables (work, focus, stress, fatigue) except for having a weak correlation with relaxation. The LF/HF ratio significantly correlates with non-thermal symptoms, even though the relationship is weak. Previous studies found that heart rate and HRV information can be indicators of stress in work activities. Previous studies also showed a positive association between increased work stress and reduced heart rate variability (HRV). Järvelin-Pasanen et al. (2018) noted a decline in RMSSD and HF power, together with an increase in the LF/HF ratio, which suggests a decrease in parasympathetic activation [30]. The utilization of an actual office environment, lacking physical activity, may perhaps explain the opposite outcomes observed in prior studies. Previous studies, on the other hand, found a correlation between HRV and high physical activity or high-concentration tasks, such as with pilots or train drivers. According to Zhang et al., heart rate reflects exercise intensity and human body metabolism [41]. Sancinelli found that HRV values have a significant correlation with students' stress during competitions and exams [31]. The weak correlation may be attributed to the relatively low physical and cognitive demands typical of the actual office setting, contrasting with a high-concentration or high-intensity occupation such as piloting, where previous studies found a stronger relationship between the LF/HF ratio and productivity. The relatively stable and moderate environmental conditions in actual office spaces, which lack significant thermal changes or stress-inducing stimuli typical of more extreme environments or controlled studies, could also contribute to this lack of correlation.

5. Conclusions

An investigation of the thermal environment, physiological data, and subjective responses was conducted in an office building in Kanagawa, Japan. The investigation collected physiological data on skin temperature, heart rate, and metabolic rate using Silmee-W22 smartwatches. Questionnaires (see Appendix A) were distributed to collect occupants' subjective responses as regards thermal sensation, thermal comfort, health, and productivity. The investigation was conducted in spring, summer, autumn, and winter. The main conclusions of this study are summarized as follows:

(a) The study found a weak but significant positive correlation between skin temperature and thermal environment variables, with the strongest relationship with indoor temperature. The correlation coefficients between skin temperature and temperature, relative humidity, and PMV are 0.34, 0.26, and 0.29, respectively. Skin temperature also showed a weak correlation with thermal sensation and comfort, and with health–productivity variables. The correlation coefficients between skin temperature and thermal sensation, thermal comfort, work progress, focus, relaxation, stress, and fatigue levels are 0.36, 0.17, −0.33, −0.34, −0.35, 0.27, and 0.29.

(b) Heart rate has no significant relationship with the thermal environment variables, thermal sensation, thermal comfort, non-thermal symptoms, stress, and fatigue levels (p-value >0.05), but it has a weak correlation with thermal symptoms (−0.2). Heart rate also significantly has a weak correlation with work progress, focus level, and relaxation level, with a coefficient correlation of −0.25, −0.19, and −0.17.

(c) LF/HF ratio has a weak correlation with temperature (−0.06) and an insignificant correlation with relative humidity and PMV (*p*-value > 0.05). The LF/HF ratio has a weak correlation with thermal sensation, non-thermal symptoms, and relaxation level, with a coefficient correlation of 0.19, 0.3, and −0.17. The LF/HF ratio insignificantly correlates with thermal comfort, thermal symptoms, work progress, focus, stress, and fatigue level (*p*-value > 0.05).

(d) Thermal environment variables have a weak relationship with thermal sensation, thermal comfort, and thermal symptoms. Thermal variables have no significant correlations with non-thermal symptoms. The temperature has the strongest correlation, with coefficient correlations between temperature and thermal sensation, thermal comfort, and thermal symptoms of 0.29, 0.37, and −0.36. Temperature, relative humidity, and PMV have an insignificant impact on work progress, focus, relaxation, stress, and fatigue levels across all seasons (*p*-value > 0.05). The limited relationship between the temperature environment and the health–productivity variables emphasizes the complex, varied character of health and productivity in an office environment. Thermal comfort enhances physical comfort; however, productivity is mainly affected by physiological, environmental, and cognitive factors. Furthermore, self-assessment techniques in measuring productivity may introduce subjective bias.

(e) Previous studies have shown a positive association between increased work stress and reduced heart rate variability (HRV), suggesting that the use of an actual office environment lacking physical activity may explain the opposite outcomes observed in prior studies. In this study, skin temperature is more accurate in predicting subjective responses to thermal responses than it is in predicting the health and productivity of office workers. The LF/HF ratio may be more accurate in predicting health and productivity in occupations that demand high concentration and physical intensity. This study demonstrates that skin temperature is a more reliable predictor of subjective thermal responses than health and productivity in actual office settings. The stable, low-intensity environment of office work may contribute to the LF/HF ratio's weak correlation with productivity, health, and thermal responses. The findings underscore the importance of conducting such studies in occupied offices to more accurately capture how IEQ influences the building occupants. This study indicates that skin temperature could be a practical tool for real-time comfort adjustment in HVAC systems.

6. Limitations and Future Works

This study was conducted in an air-conditioned building with actual office activities. The findings may be valid only for a similar environment setting. A study in non-airconditioned buildings may have different results. A limitation of this study is the lack of varied data on gender and the population due to the accessibility and availability of voluntary subjects. Subjective responses were limited because of the workload of the subjects. Further studies involving more female participants and a larger population are encouraged.

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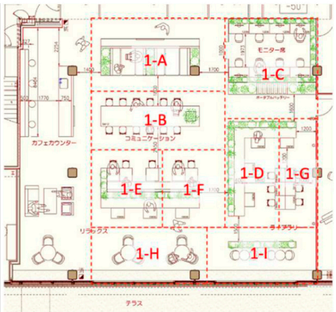
Abbreviations

HR	Heart Rate
HRV	Heart Rate Variability
MET	Metabolic Rate
PMV	Predicted Mean Vote
R^2	R-squared
ST	Skin Temperature
TSV	Thermal Sensation Vote
TCV	Thermal Comfort Vote

Appendix A. Questionnaire

No.	General Information	
1	Date and time of response	Date_________________/Time:___________
2	Age	☐~19 ☐20~24 ☐25~29 ☐30~34 ☐35~39 ☐40~44 ☐45~49 ☐50~54 ☐55~59 ☐60~64 ☐65~
3	Gender	☐Male ☐Female ☐No answer
4	Thermal sensitivity	☐Cold ☐Cool ☐Slightly Cool ☐Hot ☐ Warm ☐Slightly Warm
5	Seat Location	☐1-A ☐ 1-B ☐1-C ☐ 1-D ☐ 1-E ☐1-F ☐1-G ☐1-H ☐ 1-I
6	Type of work	☐ Paperwork ☐Generating idea ☐Communication ☐ Meeting ☐Conference ☐Small conversation ☐others:_________________________



No.	IEQ Response		10	Light Comfort	☐Comfortable ☐Slightly comfortable ☐neither ☐Slightly uncomfortable ☐Comfortable
4	Thermal sensitivity	☐Cold ☐Cool ☐Slightly Cool ☐Neither ☐Hot ☐ Warm ☐Slightly Warm	11	Light Preference	☐Darker ☐Slightly darker ☐Good as it is ☐Slightly brighter ☐Brighter
5	Humidity	☐Feel Damp ☐**Feel Slightly damp** ☐Dry ☐**Slightly dry** ☐ Feel none	12	Odor/unpleasant smell	☐yes ☐no
6	Airflow	☐ Feel none ☐ Slightly feel it ☐ Feel it ☐ Feel it strongly	13	IAQ Satisfaction	☐ Satisfied ☐Slightly satisfied ☐neither ☐ Slightly dissatisfied ☐Dissatisfied
7	Thermal Comfort	☐ Comfortable ☐Slightly comfortable ☐neither ☐ Slightly uncomfortable ☐Comfortable	14	Acoustic/Noise	☐yes ☐no
8	Thermal Preference	☐Cooler ☐Slightly cooler ☐Good as it is ☐Slightly warmer ☐Warmer	15	Acoustic Satisfaction	☐ Satisfied ☐Slightly satisfied ☐neither ☐ Slightly dissatisfied ☐Dissatisfied
9	Light Brightness	☐Dark ☐Slightly dark ☐slightly bright ☐bright	16	Source of noise	☐People ☐own voice ☐AC ☐outside traffic ☐Equiptments ☐others:________________
	Productivity (higher score means better performance)			Health (lower score means better performance)	
17	Work progress 0= no progress 10= progress well	0 - 1 - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10	22	Stress Level 0:No stress 10: Very stressful	0 - 1 - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10
18	Focus level 0= no focus 10= very focus	0 - 1 - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10	23	Fatigue 0:No fatigue 10: Very tired	0 - 1 - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10
19	Relaxation level 0= no relax et all 10= very relax	0 - 1 - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10	24	Stress Factors	☐thermal environment ☐IAQ ☐Interior ☐light environment ☐Acoustic ☐Others
20	Factors support productivity	☐thermal environment ☐light environment ☐IAQ ☐Acoustic ☐Interior ☐Others	25	Thermal Symptoms	☐Sweating ☐Cold hands ☐Cold feet ☐Chill in upper body ☐chills in lower body ☐burning body ☐others:___________
21	Physical Condition 0= no good 10=very good	0 - 1 - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10	26	Non-thermal Symptoms	☐headache ☐sluggishness ☐tired eyes ☐Stiff shoulders ☐Backhurts ☐Sleepy ☐others:________________________

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