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Investigation of the relationships among temperature, illuminance and sound level, typical physiological parameters and human perceptions

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ABSTRACT

Human perceptions are stimulated simultaneously by multiple environmental factors, such as temperature, illuminance, and sound level. Meanwhile, the human body regulates physiological parameters to maintain balance with changes in the indoor environment. This means that human perceptions can be expressed as a function of typical physiological parameters that vary with the ambient environmental conditions. Therefore, a series of human subject experiments were conducted under 144 controlled indoor environment conditions. Human perception and five physiological parameters, i.e., systolic blood pressure, diastolic blood pressure, heart rate, and skin temperatures at the wrist and forehead, under stimulation by different combinations of temperature, illuminance, and sound level, were measured to determine whether any physiological parameters are affected by environmental factors, and if so, then which parameters. The experiments were also conducted to identify which physiological parameter generated the greatest amount physiological information that could be used to represent the human perception. The study revealed that physiological parameters were affected to varying degrees by multiple environmental factors and had different degrees of correlation with human comfort votes. Moreover, the measured skin temperature at the wrist (STwrist) varied linearly with the air temperature (t) and exhibited an S-shaped relationship with thermal comfort vote (TC). In addition, the quantitative relationships between t and STwrist and between TC and STwrist were established. By combining these two quantitative relationships, the temperature ranges and acceptance rates under different thermal comfort vote ranges were obtained, which coincide with the results of previous research and satisfy the requirements of ASHRAE Standard 55–2010.

1. Introduction

As the development of society progresses, people are spending more of their time (approximately 80–90% at present [1]) inside buildings. The indoor environment affects human perception [2], which has a significant influence on human performance [3,4]. Therefore, it is of great significance to find out how the indoor environment affect human perception and provide a satisfied indoor environment.

1.1. Human comfort vs. multiple indoor environmental stimuli

Occupants are simultaneously exposed to multiple indoor environmental stimuli, including temperature, illuminance, sound level, and air quality [5]. The effect of the indoor environment on human perception depends not only on individual aspects but also on their combined effect [6,7]. This means that multiple environmental factors should be considered simultaneously when investigating the relationship between human perception and the indoor environment. However, reviewing recent studies in this field of research reveals that most of the investigations have focused on the separate effects of single environmental factors, i.e., the thermal [8,9], acoustic [10], visual environment [11–14] and air quality factors [15], on human perception. Few studies [5,7] have focused on the relationships between multiple indoor environmental factors and human perception.

Wu H et al. [7] collected thirty research articles [16–45] published since 2000 and focused on i) the effect of a single environmental factor (i.e., the acoustic, thermal, or visual environment) on perception or performance, and ii) the coupled effects of two or three environmental

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factors on perception and performance. The results obtained in these studies generally differed. For instance, when investigating the coupled effect between environmental factors and human perception, some researchers found that the illuminance level had an effect on thermal perception [23,26,27,32], while others came to the opposite conclusion [40,42]. Moreover, the quantitative relationships between human comfort and indoor environmental factors, that can be used to predict human comfort based on the obtained environmental factors are different. For example, in the quantitative relationships between acoustic satisfaction and sound level, the calculated neutral sound levels were 49.6 dB (Huang et al. [29]), 59.51 dB (Guo et al. [28]), and approximately 71.19 dB (Wong et al. [20] and Fassio et al. [22]). These differences are likely a result of the biological differences of occupants, classification of perception in the questionnaires, and human factors of individual occupants, e.g., their metabolic rate, clothing, and national area. Therefore, it is necessary to investigate human comfort systematically using objective data.

1.2. Human comfort vs. physiological parameters

It is well known that physiological regulation will occur with changes in environmental factors, which will cause fluctuations of human physiological parameters. Accordingly, physiological parameters have the potential to act as a bio-signal for investigating human comfort in multiple indoor environments. In other words, human physiological parameters, which are affected by multiple environmental factors, are related to the human factors of individual occupants. Some of these parameters also have a strong correlation with human perceptions. For instance, the human thermoregulation system controls skin temperature through vasodilatation and vasoconstriction to maintain thermal comfort when the air temperature changes [46]. As a result, skin temperature has considerable potential for assessing thermal comfort, as has been demonstrated by many researchers [47–50]. Apart from skin temperature, the heart rate [51,52], blood pressure [53,54], electrocardiogram [55], and other related physiological parameters have also been used to predict thermal comfort. Moreover, it should also be noted that occupants are subjected to multiple environmental factors, and consequently different environmental factors will have impacts on physiological parameters and lead to different individual human perceptions. Dehghan H et al. [33] ound that the mean change in blood pressure was significantly different before and after exposure to heat. However, few studies have focused on the relationships between physiological parameters and individual human perception under multiple environmental stimuli. While the relationships between air temperature, some physiological parameters, and thermal comfort are well-known, the relationships among other environmental factors, physiological responses, and occupant perception require further research.

Furthermore, understanding the relationships between environmental factors, physiological parameters, and human comfort will be beneficial for energy savings. In recent years, the development of intelligent wearable devices has made real-time monitoring of human physiological parameters possible. For example, wearable fitness trackers have become broadly available, such as Fitbit (Fitbit Inc., U.S.), Apple Watch (Apple Inc., U.S.) and Garmin (Garmin Ltd., U.S.). The emerging sensing provide the opportunities to apply the measured data to infer human comfort [56]. More recent studies, especially those conducted at the Center for the Built Environment at the University of California [57,58], have explored individual comfort models based on wearable devices, including physiological parameters from which human perceptions can be predicted. The researches have shown that wearable device will address variability in individuals' thermal comfort [59]. Li W et al. [60] also used a wristband device to monitor and evaluate human thermal sensations. These studies make it possible to realize the adjustment of environmental factors based on physiological signals. For instance, Nagy et al. [61] controlled artificial lights based on occupancy sensor data acquired from wearable devices, with which it was possible to achieve energy savings of greater than 30% compared to manual switching.

1.3. Our study

This study aims to investigate the problem of human comfort stimulated by multiple environmental factors simultaneously using typical physiological parameters. To reduce the complexity of the research, this study excluded indoor air quality from the experimental factors and focused on the relationships between the thermal, acoustic, and luminous environments and typical physiological parameters and human perceptions, i.e., thermal comfort, acoustic comfort, and visual comfort. A series of experiments involving 35 human subjects was conducted in a climate chamber under $6 \times 6 \times 4 = 144$ (temperature × illuminance intensity × sound level) controlled indoor environment conditions.

Reviewing the typical literature [46–64] adopting physiological parameters in studying thermal comfort, approximately 1/3 of the studies investigated the interaction between skin temperature and thermal comfort, followed by investigations utilizing the heart rate (approximately 23.33%), blood pressure (approximately 23.33%), electrocardiograms (approximately 13.33%), and other related physiological parameters (approximately 13.33%) including electroencephalograms, skin conductivity, and oxygen saturation. Therefore, the systolic blood pressure, diastolic blood pressure, heart rate, and skin temperature at the wrist and forehead were measured in this study.

2. Methods

2.1. Indoor climate chamber

The experiment was conducted in the heating chamber of a climate chamber at Harbin Institute of Technology (HIT). As shown in Fig. 1, the full climate chamber consists of a cooling chamber and a heating chamber intended to resemble an indoor or outdoor environment. Both the cooling chamber and heating chamber can move along tracks to work either simultaneously or independently. The experiment was conducted in the heating chamber, which has an experimental area of 4.2 m × 4.2 m × 3.1 m (length × width × height). During the experiment, the cooling chamber was not connected to the heating chamber. To ensure the stability of the environmental conditions in the climate chamber, the walls are made of polystyrene foam composite boards with high-performance insulation and the doors are thermally and acoustically sealed with gaskets.

The climate chamber is equipped with an HVAC system. The HVAC system is able control the air temperature within ±0.5 °C of the set-point within the range of 0–40 °C and the relative humidity within ±2% of the set-point within the range of 20%–90%. The chamber was windowless. The visual and acoustic environment of the chamber was controlled using artificial lighting and loudspeakers. As presented in Fig. 2 and Fig. 3, a table and six chairs were located at the center of the chamber. The table has dimensions of 1.4 m × 1.4 m × 0.9 m. Moreover, a ceiling-

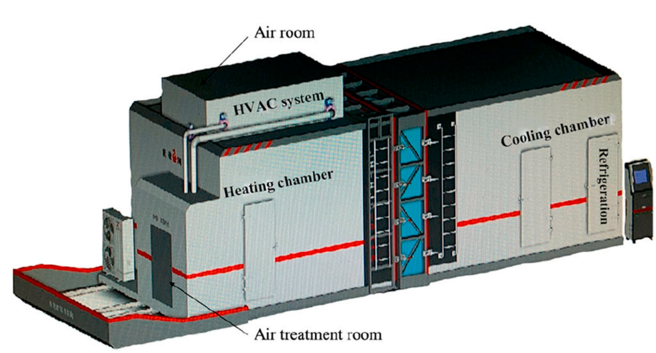


Fig. 1. Climate chamber at HIT.

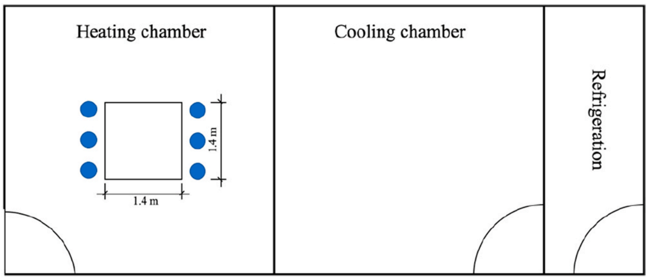


Fig. 2. Floor plan of climate chamber at HIT.

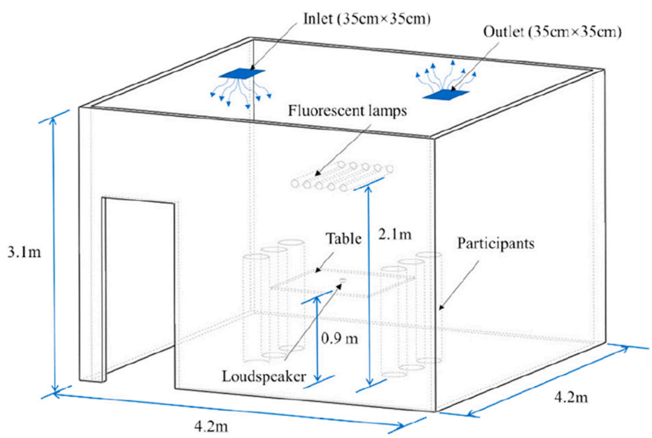


Fig. 3. Dimension and layout of the chamber.

supply displacement ventilation system was utilized in the climate chamber. Similar to an overhead system, a supply inlet and an exhaust outlet with dimensions of 35 cm × 35 cm are located on the ceiling, which produce a ceiling-to-ceiling airflow pattern, as shown in Fig. 4.

2.2. Experimental conditions

Based on the field studies conducted by Bin Cao et al. [16], the ranges of the operative temperature, illumination intensity, and A-weighted sound level in public buildings in Beijing and Shanghai are 16.6–30.3 °C, 140–2150 Lux, and 39–56 dBA, respectively. To stimulate realistic and typical environmental conditions, a total of 6 × 6 × 4 = 144 controlled indoor environment conditions were produced by considering 6 temperature conditions, 6 illuminance conditions, and 4 acoustic conditions. Six temperatures—18 °C, 20 °C, 22 °C, 24 °C, 26 °C, and 28 °C—were maintained through the HVAC system. The supply airflow rate was automatically controlled by a computer based on the indoor temperature in the chamber. For each ambient temperature, a constant relative humidity of 40% was maintained, and air velocities at the participants' positions were measured to be less than 0.1 m/s, as suggested by ASHRAE-55 [65]. Six illuminance conditions with illuminance intensities of 180, 300, 570, 840, 1110, and 1380 Lux were manually controlled through artificial lighting. Five ceiling-mounted fluorescent lamps installed at the top of the table were used to provide five luminous environments by turning on 1, 2, 3, 4, or 5 lights to provide 300, 570, 840, 1110, and 1380 Lux, respectively. In addition, there was an artificial light fixed in the ceiling of the chamber. The ambient illumination level of the chamber (180 Lux) provided by this artificial light was also considered. Meanwhile, white noise-simulating background noise was used to create four acoustic conditions (35, 45, 55, and 65 dB). A loudspeaker placed at the center of desk was used as the sound source. The arrangement of the test chamber is shown in Figs. 3 and 4.

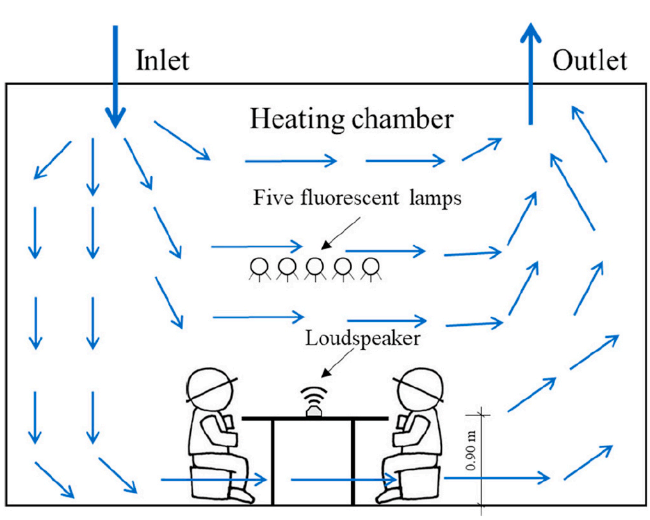


Fig. 4. Ceiling-supply displacement ventilation system.

2.3. Experimental measurements

2.3.1. Physical measurements

The indoor environmental parameters, including the air temperature, wet-bulb globe temperature (WBGT), airflow velocity, relative humidity, sound level, and illuminance intensity, were measured at a height of 1.1 m, and were adjusted to meet the target setup conditions. It should be noted that the participants were present during the air speed measurements. A hand-held hot wire anemometer was used to measure the air speed approximately 10 cm from the cheek at a height of approximately 1.1 m. The instruments utilized to measure the physical environmental parameters are summarized in Table 1.

2.3.2. Physiological measurements

Cardiovascular-related physiological parameters, including the systolic blood pressure (SBP), diastolic blood pressure (DBP), heart rate (HR), and skin temperature, were monitored in this study. In the experiment, the skin temperatures at two easily measurable locations were considered: the wrist (STwrist) and forehead (STforehead). The blood pressure and heart rate were measured using an electronic sphygmomanometer (OMRON U10L: for blood pressure, range: 0–299 mmHg, accuracy: ± 3 mmHg; for heart rate, range:40–180 beats/min, accuracy: ± 5%). In addition, an OMRON MC-872 J electronic thermometer (range: 0–50 °C, accuracy: ± 0.3 °C) was used to measure the skin temperature.

2.3.3. Subjective measurements

Human subjective sensations were recorded through a questionnaire that included comfort and satisfaction assessments of the indoor temperature, illuminance, background noise, and overall environment. As shown in Fig. 5 and Fig. 6, the human comfort assessments, namely thermal comfort, acoustic comfort and visual comfort, were evaluated on a 7-point numeric scale; the human satisfaction assessments, namely acoustic satisfaction, thermal satisfaction, visual satisfaction and overall satisfaction, were evaluated on a 3-point numeric scale.

Table 1
Information of instruments.

Parameters	Instrument	Range	Accuracy
Air temperature	AZ8778	0–50.0 °C	0.1 °C
Relative humidity		0–100%	0.1% R.H
WBGT		0–80.0 °C	0.1 °C
Illuminance intensity	TES 1339	9999 Lux	0.01 Lux
Sound level	TES 1357	30 dB–130 dB	1.5 dB
Airflow velocity	TES 1340	0.1–30.0 m/s	0.01 m/s

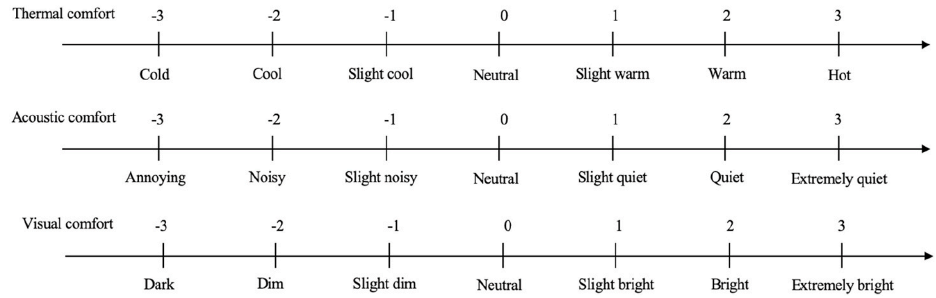


Fig. 5. The scale of human comfort levels.

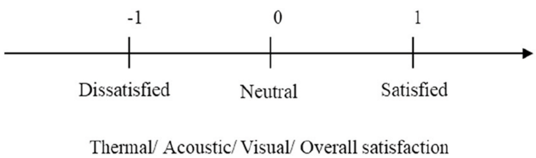


Fig. 6. The scale of human satisfaction levels.

2.4. Participants

A total of 35 university students (27 men and 8 women) volunteered and participated in the experiment free of charge. Their personal details were collected and are presented in Table 2. The participants had been informed of the nature of the study in advance. None of the participants was a smoker, consumed excessive alcohol, or was regularly under medication. In accordance with ASHRAE Standard 55 [65], all the participants were asked to wear a clothing ensemble of approximately 0.75 clo, which typically consists of a pair of straight trousers, a long-sleeved shirt, a pair of socks, underwear, a T-shirt, and sports shoes.

A type of power analysis, noted to be an 'A Priori' analysis, was performed to determine the sample size, in accordance with a study conducted by Guan H et al. [63]. According to this 'A Priori' analysis, when a statistical model is defined, the relationship between the sample size, N, statistical power level, 1-β, significance level, α, and expected effect size, f, can be determined. To obtain a proper sample size, N, the other three parameters should be determined.

Assuming a total sample size needed to achieve a statistical power of 95% in testing the effects of indoor environmental factors at an α level of 0.05, then based on the experimental conditions, the total number of groups in this scenario is 144. When determining the expected effect size, f, typical studies were referenced. Choi J H et al. [51] and Hui Zhu [55] et al. have presented a significant relationship between environmental factors and physiological parameters. Soebarto V A et al. [47], Wang Z et al. [49] and Choi J H et al. [64] also demonstrated a significant correlation between physiological parameters and human comfort. We thus used the conventional value of $f = 0.25$ defined by Cohen [66] as a large effect. The G*Power [67,68] was used to determine the sample size, and a total sample size of 380 was calculated. To ensure equal group sizes, 380/144 = 2.64 was rounded to a multiple of 144 by adopting a total sample size of $144 \times 3 = 432$. This means that for each experimental condition, there should be at least three subjects participating. In our study, 6 subjects participated in each experimental condition.

Table 2
Details of participants.

	Mean (S.D.)	Max	Min
Age	23.91 (1.48)	27	20
Height (cm)	174.24 (7.43)	186	160
Weight (kg)	67.6353 (12.57)	95	44
BMI	22.15 (3.13)	31.1	17.2

2.5. Experiment procedure

The target $6 \times 6 \times 4 = 144$ controlled indoor environment conditions were divided among 36 test groups. For each designated test group, there were four different controlled environments. The temperature and illuminance intensity were identical, and the sound level was randomly assigned as 35, 45, 55, or 65 dB. The specific environment parameters have been provided in Supplement material. Meanwhile, 6 of the 35 participants were required to participate in each test group. Every participant could choose to take part in more than one test group. Throughout the experiment period, the participants were sedentary and could carry out some light office activities, such as reading books or surfing the Internet (equivalent to a metabolic rate of approximately 1.2 Met). Eating, speaking, drinking, listening to music, and watching videos were forbidden. All the subjects were unaware of the environmental factors that they were experiencing.

To ensure a steady room air temperature, each thermal condition was set at least 2 h prior to the test. In previous research, Chow et al. [69] found that 30 min was adequate to achieve a steady thermal sensation after a change in environmental conditions; Tang et al. [70] found that the average time for loudness adaptation was 82 s. It takes approximately 5 min for the eye to adapt from darkness to bright sunlight [71]. Therefore, in each of the 70-min-long test groups (as shown in Fig. 7), a 30-min adaptation period was implemented at the beginning of the test to allow for thermal and visual adaptation, which is in accordance with prior research [27,29]. Once the sound level was changed, a 5-min acoustic adaptation period was allowed. Thereafter, the subjects were asked to assess their perceptions via questionnaires, and their physiological parameters were measured in 5 min. A total of 24 questionnaires for 4 different sound levels were distributed to each test group. A total of $24 \times 36 = 864$ questionnaires were collected.

2.6. Statistical analysis

A factorial analysis of variance (ANOVA), which was also used by Wonyoung Yang et al. [27], was conducted to test the relationships between multiple environmental factors, i.e., the temperature, illuminance, and sound level, and the measured physiological parameters. The null hypothesis was that there is no significant difference in the dependent variable, e.g., the systolic blood pressure, based on the independent variable at several levels, e.g., the temperature. The alternative hypothesis was that there is a significant difference in the dependent variable, e.g., the systolic blood, pressure based on the independent variable at several levels, e.g., the temperature. Each analysis was performed at a 95% significance level. This means that the null hypothesis would be accepted when $P < 0.05$. Otherwise, the alternative hypothesis would be accepted.

Moreover, the magnitude of the effects of each independent variable on the dependent variables was also measured using the partial eta squared (η_p^2). η_p^2 represents the proportion of variance accounted for by some effect. Here, $\eta_p^2 = SS_{effect}/(SS_{effect} + SS_{error})$, where SS is short for "sum of squares" or the amount of dispersion in the dependent variable.

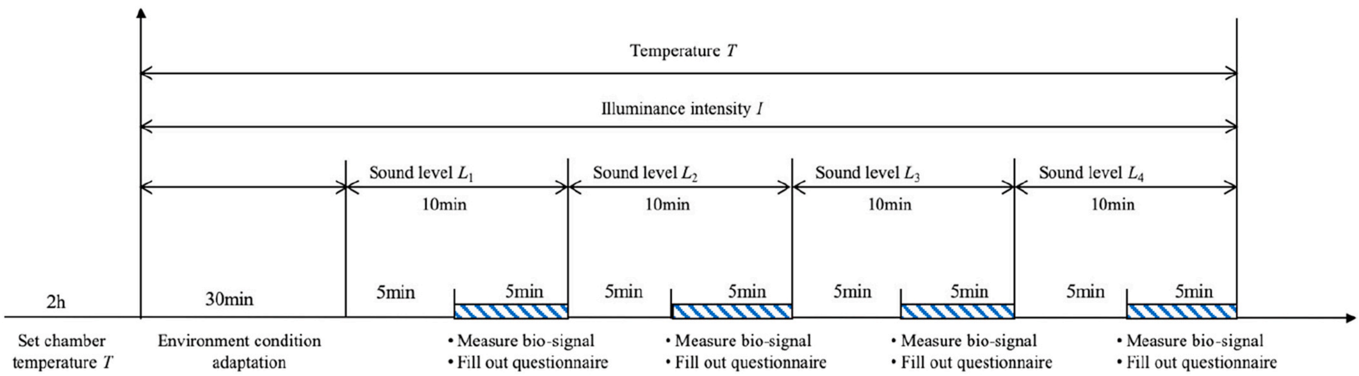


Fig. 7. Experimental procedure of a test group.

This means that η_p^2 represents the variance attributable to an effect divided by the variance that could have been attributable to this effect. η_p^2 was used to compare the magnitude of the effect.

An ANOVA test can indicate whether results are significant overall, but it cannot pinpoint exactly where those differences lie. The Tukey Test (or Tukey procedure), also called Tukey's honest significant difference (HSD) test, is a post-hoc test based on the studentized range distribution. After an ANOVA test has been conducted and significant results have been obtained, Tukey's HSD can be adopted to determine which specific groups' means differ (compared with each other). The test compares all possible pairs of means. To test all pairwise comparisons among the means using the Tukey HSD, the HSD for each pair of means is calculated using the following equation:

$$HSD = \frac{M_i - M_j}{\sqrt{\frac{MS_w}{n}}} \tag{1}$$

where $M_i - M_j$ represents the difference between the pair of means, in which M_i should be larger than M_j; MS_w is the mean square within; and n is the number in the group or treatment.

Subsequently, a tabulated value in Tukey's critical value table can be found according to the level of significance. The calculated HSD is then compared with this tabulated value. If the calculated HSD is greater than the critical value in the table, the two means are significantly different and will be placed into separate subsets. This Tukey's HSD test was applied to determine the means that were significantly different from each other in our study. Moreover, the number of subsets obtained using Tukey's HSD test was used to divide the effects of environmental factors on the physiological parameters into different levels (according to the relative size to the level of the independent variable).

Analysis of the relationships between human comfort and the measured physiological parameters also followed the statistical analysis procedure outlined above.

Moreover, there are main effects and interaction effects between the independent variables and dependent variables. The main effect is used to explain the impact of a single independent variable (e.g. SBP, DBP, HR) on a dependent variable (e.g., R = thermal comfort), whereas the interaction effects represent the coupled effects of two or three independent variables (e.g., SBP*DBP or DBP*HR) on a dependent variable (e.g., R = thermal comfort). To reduce the research complexity, we aimed to appraise the influence of all the selected variables in the most interpretable manner possible. Therefore, only the main effects, not the interaction effects, were first considered in this study.

3. Results

3.1. Environmental factors and physiological parameters analyses

The distributions of physiological parameters under different environmental conditions are shown in Fig. 8, Fig. 9 and Fig. 10. A minute fluctuation in DBP was observed with the change in temperature.

The means of the SBP, HR, and $ST_{forehead}$ were moderately different under different temperatures. The mean of the ST_{wrist} was clearly different under different temperatures, exhibiting a strong linear relationship. In addition, the SBP and the $ST_{forehead}$ demonstrated an inversely proportional relationship with the temperature, while the HR and the ST_{wrist} demonstrated a proportional relationship with the temperature. As for the distributions of physiological parameters under different illumination conditions, except for the ST_{wrist}, the four other physiological parameters exhibited a tiny fluctuation with the change of illumination. A higher ST_{wrist} was reported by people exposed to dimmer light than by people exposed to brighter environments. We assume that this finding may be related to the thermal expectations induced by light intensity. Moreover, there were tiny fluctuations in all the measured physiological parameters under different sound levels, which indicates that the sound level had a slight effect on the physiological parameters.

It should be noted that the environmental factors, which are usually continuous numerical variables in our daily life, are discrete variables in this study, e.g., air temperatures of 18 °C, 20 °C, 22 °C, 24 °C, 26 °C, and 28 °C. In contrast, the physiological parameters are continuous numerical variables. Therefore, the factorial ANOVA and partial eta squared were applied to analyze the effects of environmental factors on the physiological parameters. The results are presented in Table 3. The mean square in the table is calculated by dividing the sum of the square for each estimate of variance by the degrees of freedom of the dependent variables. The degrees of freedom of the dependent variables are calculated by subtracting one from the number of levels of the source.

As mentioned in Section 2.6, $P < 0.05$ indicates that the physiological parameters are statistically significant and represents the probability that the results are different. Accordingly, bold text is used in Table 3 when $P < 0.05$. As indicated in Table 3, the changes in all the measured physiological parameters with the change in temperature were statistically significant. Combined with the results of η_p^2, the temperature was shown to have the greatest effect on ST_{wrist} (0.624 > 0.089 > 0.078 > 0.069 > 0.020). The results also revealed statistically significance differences between the DBP, the HR, the ST_{wrist}, the $ST_{forehead}$ under different groups of illuminances. Although the magnitude of the effect of illuminance on the ST_{wrist} was the greatest, it was relatively smaller than that of the effect of temperature on the ST_{wrist} (0.624 > 0.068). Moreover, the results showed that with the change in sound level, only the change in the ST_{wrist} was statistically significant. Furthermore, the sound level was observed to have a relatively slight effect on the ST_{wrist} ($\eta_p^2 = 0.009$). The results of the factorial ANOVA and partial eta squared are consistent with the tendencies indicated in Figs. 8, Figs. 9 and 10.

To determine exactly where the differences lie, for the physiological parameters with $P < 0.05$ in Table 3, the means and post-hoc Tukey HSD test results are listed in Table 4. With the change in the environmental

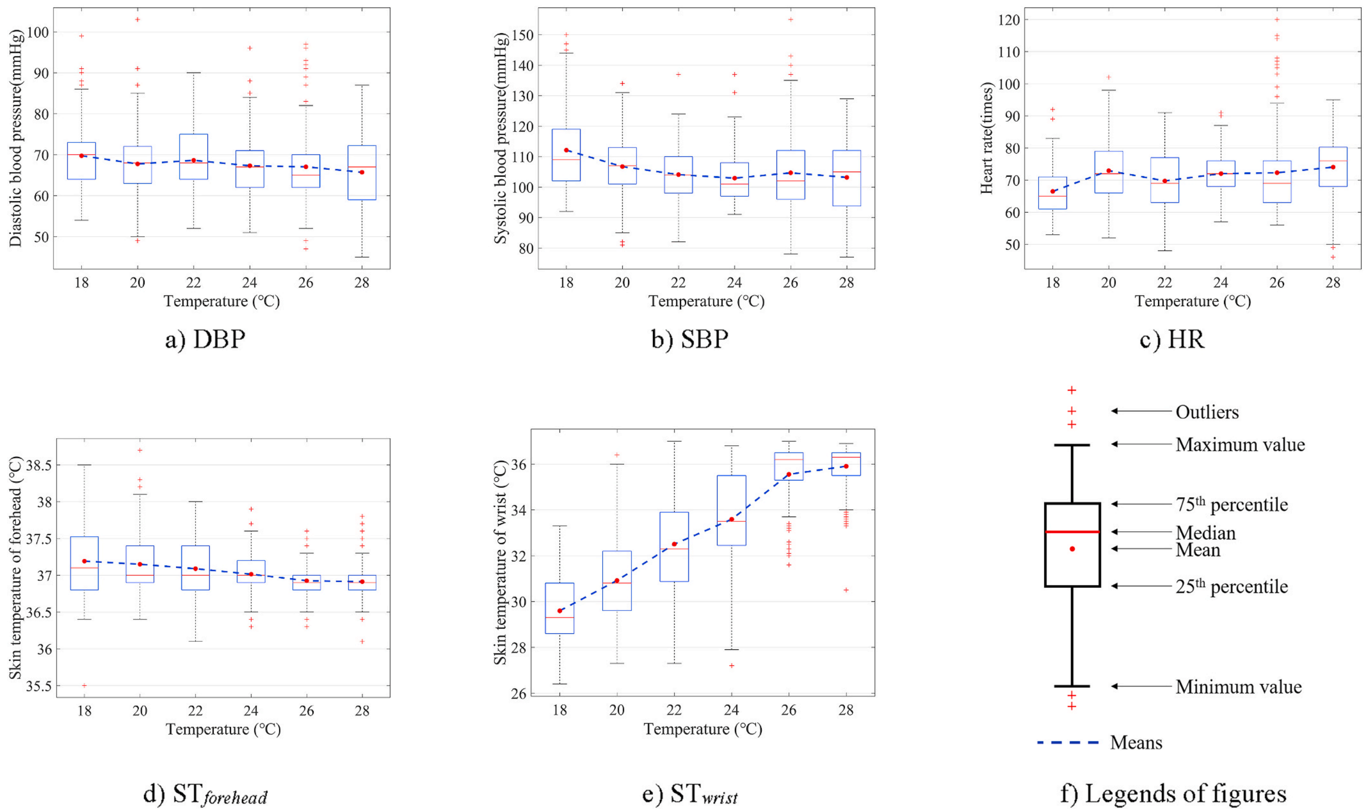


Fig. 8. Distributions of physiological parameters under different temperature.

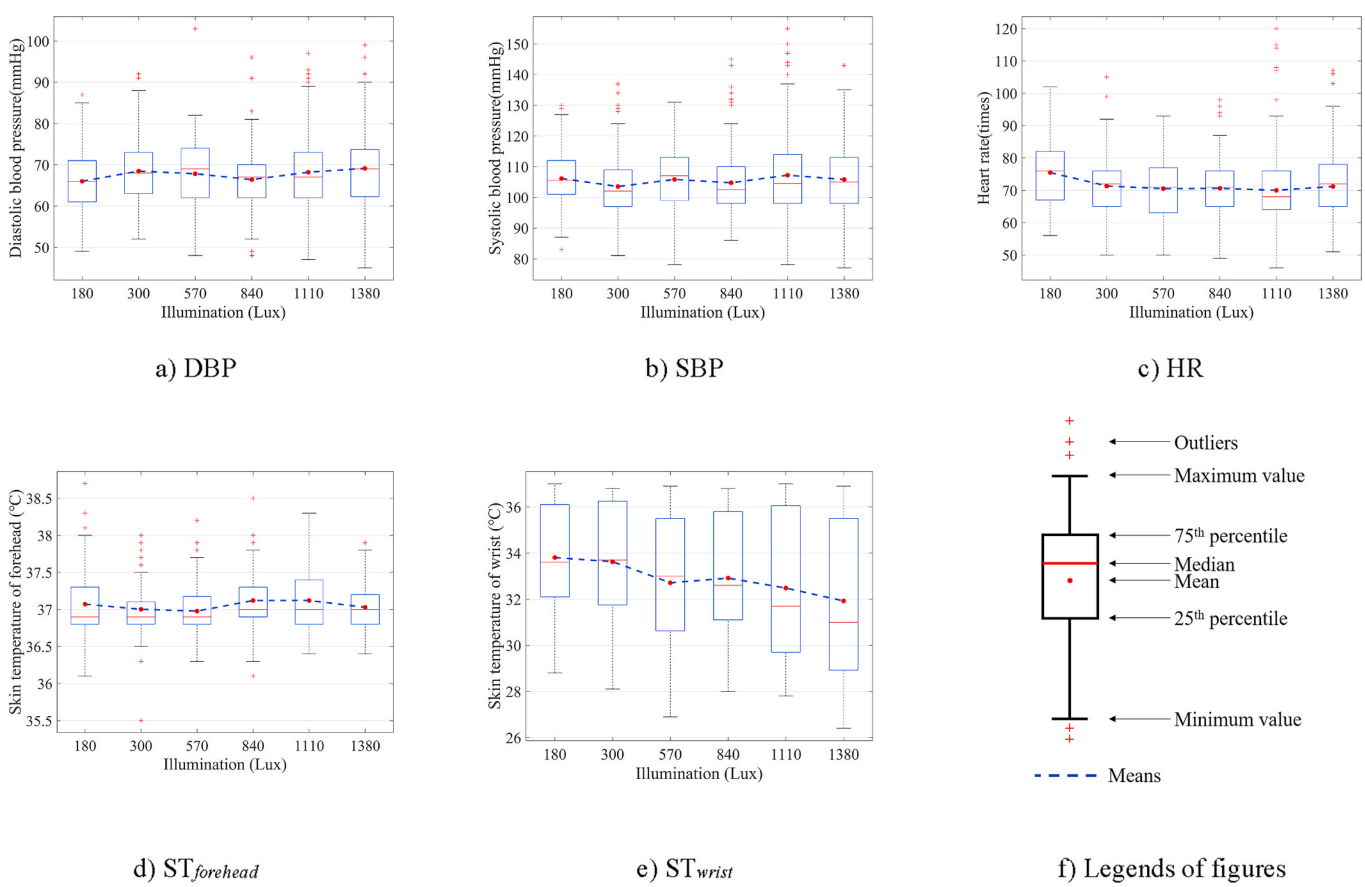


Fig. 9. Distributions of physiological parameters under different illumination.

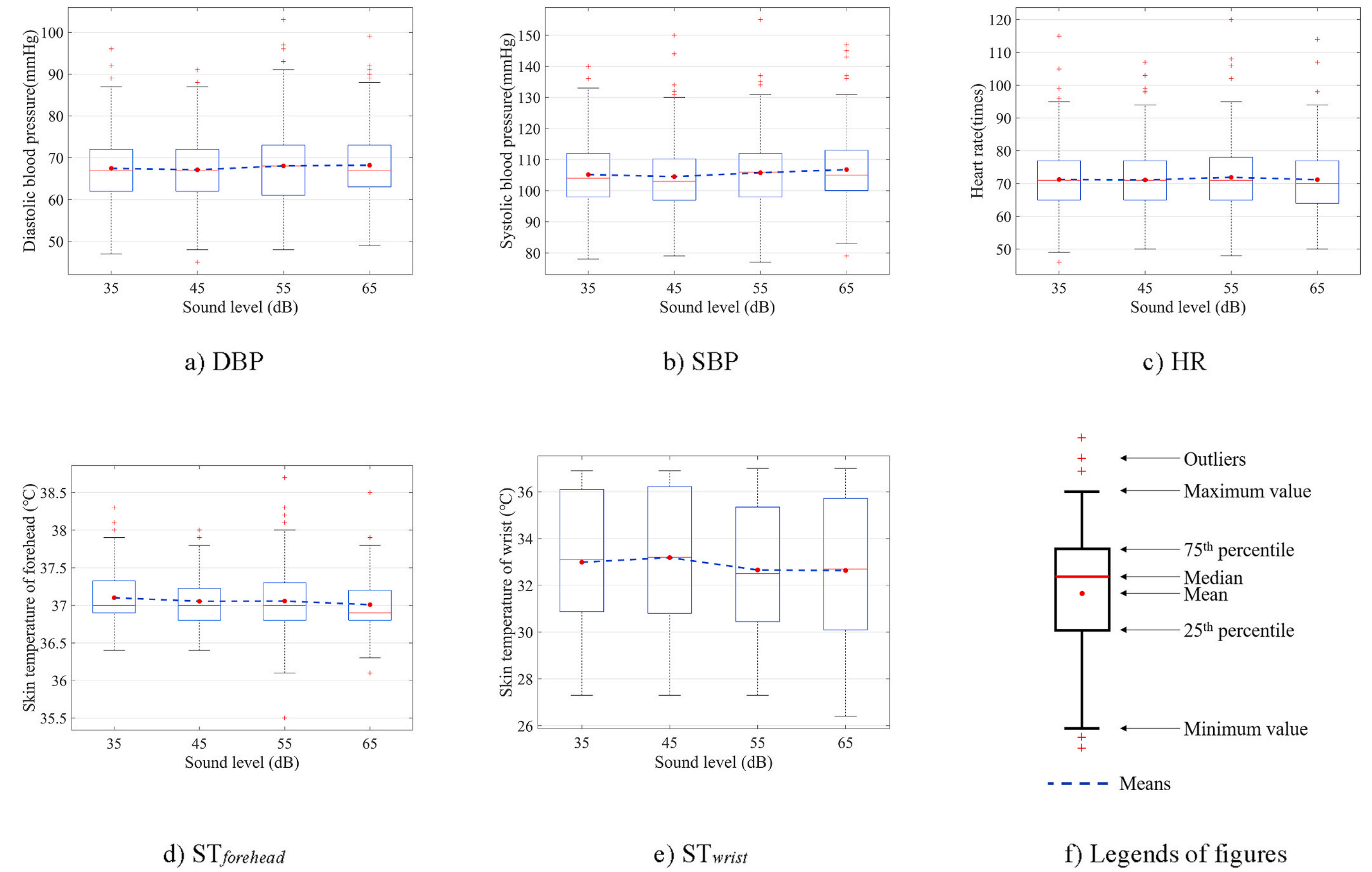


Fig. 10. Distributions of physiological parameters under different sound level.

Table 3
Result of factorial ANOVA of environmental factors and physiological parameters (bold text when $P < 0.05$).

Source	Dependent Variable	Mean Square	F	P	η_p^2
Temperature	SBP	1557.443	13.487	**.000**	.069
	DBP	256.742	3.809	**.002**	.020
	HR	1578.948	17.917	**.000**	.089
	ST_{wrist}	880.149	303.065	**.000**	.624
	$ST_{forehead}$	1.889	15.395	**.000**	.078
Illuminance	SBP	201.963	1.749	.121	.009
	DBP	214.122	3.177	**.008**	.017
	HR	338.171	3.837	**.002**	.021
	ST_{wrist}	38.573	13.282	**.000**	.068
	$ST_{forehead}$	.529	4.308	**.001**	.023
Sound level	SBP	133.970	1.160	.324	.004
	DBP	47.708	.708	.547	.002
	HR	10.228	.116	.951	.000
	ST_{wrist}	8.235	2.836	**.037**	.009
	$ST_{forehead}$	.302	2.457	.062	.008

factors, the subsets of different physiological parameters were generally different.

If the means for two groups are shown in different subsets, there is statistically significant evidence of a difference between their mean values. For example, the number of subsets for the DBP physiological parameter was two. The mean DBP when the temperature was 26 °C appears in a subset by itself and does not appear in any other subsets. This indicates that the mean DBP when the temperature was 26 °C was significantly different from the mean DBP values under all the other temperatures conditions. If the means for two groups appear in the same subset, there is no statistically significant evidence that their mean values differ. For example, the DBP values for temperatures of 18 °C, 20 °C, 22 °C, and 24 °C appear together in a subset. This indicates that the mean DBP values in these four temperatures groups did not differ significantly.

To clarify the magnitudes of the effects of different environmental factors on the physiological parameters, we divided them into three levels according to the number of subsets and the results mentioned above.

1) Obvious effect (number of subsets = 5): air temperature obviously affects the ST_{wrist};
2) Moderate effect (number of subsets = 3–4): air temperature moderately affects the SBP, the HR and the $ST_{forehead}$; Illuminance moderately affects the ST_{wrist};
3) Slight effect (number of subsets = 2): air temperature slightly affects the DBP; Illuminance slightly affects the DBP, the HR and the $ST_{forehead}$; Sound level slightly affects the ST_{wrist}.

3.2. Human comforts and physiological parameters analyses

Distributions of the physiological parameters under different human comfort votes are presented in Fig. 11, Fig. 12 and Fig. 13. For the physiological parameters under different thermal comfort votes, the fluctuations in DBP and HR were relatively minute. The ST_{wrist} exhibited a clear S-shaped relationship with the thermal comfort vote. It also can be observed that $ST_{forehead}$ exhibited a proportional relationship to thermal comfort, which indicates that $ST_{forehead}$ was lower when the participants felt cold and higher when the participants felt warm. SBP exhibited the opposite trend to that of $ST_{forehead}$. Moreover, there were no regular fluctuations observed between any of the measured physiological parameters and different visual or acoustic comfort votes.

The human comfort votes are discrete variables, and the

Table 4
Means and post hoc Tukey HSD test results (that do not share a letter are significantly different; A < B < C < D < E).

Environmental factors		N	SBP		DBP		HR		ST_{wrist}		$ST_{forehead}$	
Temperature (°C)	18	144	112.179	C	69.644	B	66.368	A	29.711	A	37.179	C
	20	144	106.626	B	67.713	A, B	71.317	B, C	30.938	B	37.154	C
	22	144	104.099	A, B	68.689	B	68.655	B	32.452	C	37.084	C, B
	24	144	103.035	A	67.260	A, B	74.167	C, D	33.590	D	37.019	B, A
	26	144	104.605	A, B	66.962	A, B	74.825	D	35.610	E	36.924	A
	28	144	103.241	A	65.733	A	74.004	C, D	35.903	E	36.910	A
	Subset		3		2		4		5		3	
Illuminance (Lux)	180	144			66.295	A	74.748	B	33.444	C	37.077	A, B
	300	144			68.596	A, B	71.508	A	33.361	C	37.010	A
	570	144			67.846	A, B	70.838	A	33.039	B	36.958	A
	840	144			66.212	A	70.481	A	33.302	B	37.106	B
	1110	144			67.917	A, B	70.559	A	32.985	B	37.099	B
	1380	144			69.135	B	71.203	A	32.072	A	37.022	A, B
	Subset				2		2		3		2	
Sound level (dB)	35.00	216							33.261	A, B		
	45.00	216							33.106	B		
	55.00	216							32.933	A		
	65.00	216							32.836	A		
	Subset								2			

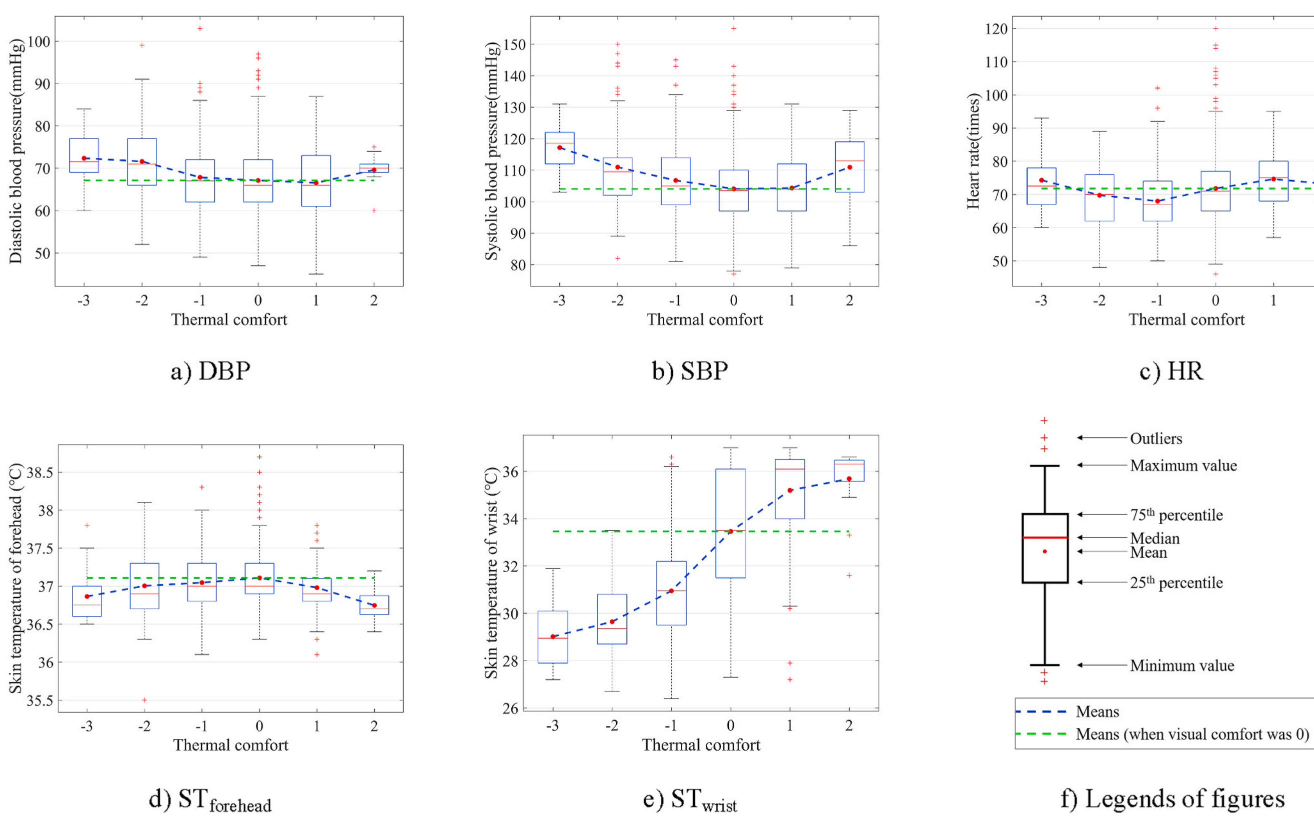


Fig. 11. Distributions of physiological parameters under different thermal comfort.

physiological parameters are continuous numerical variables. Thus, factorial ANOVA was also carried out to determine the statistical significance of physiological parameters under different comfort scores, and the results are presented in Table 5. The meaning of the mean square is the same as that in Table 3. Similarly, bold text is also used in Table 5 to indicate $P < 0.05$.

As can be seen, all the measured physiological parameters under different thermal comfort votes were statistically significant. The difference in the ST_{wrist} under different thermal comfort votes was the greatest, with an $\eta_p{}^2$ of 0.383 (0.383 > 0.087 > 0.058 > 0.038 > 0.029). In addition, all the measured physiological parameters under different visual comfort votes were statistically significant. However, the magnitudes of the effects of each visual comfort vote on the physiological parameters were relatively minor, with $\eta_p{}^2$ values of less than 0.04. Moreover, $ST_{forehead}$ was the only parameter that was statistically significant with different acoustic comfort votes. The results of the factorial ANOVA also indicate that the studied physiological parameters (SBP, DBP, HR, ST_{wrist}, and $ST_{forehead}$) under specific environmental conditions may generate physiological information that can be used to represent thermal comfort and visual comfort, and there might be a correlation between acoustic comfort and $ST_{forehead}$.

To determine exactly where those differences lie, for the physiological parameters with $P < 0.05$ in Table 5, the means and post-hoc Tukey HSD test results are listed in Table 6.

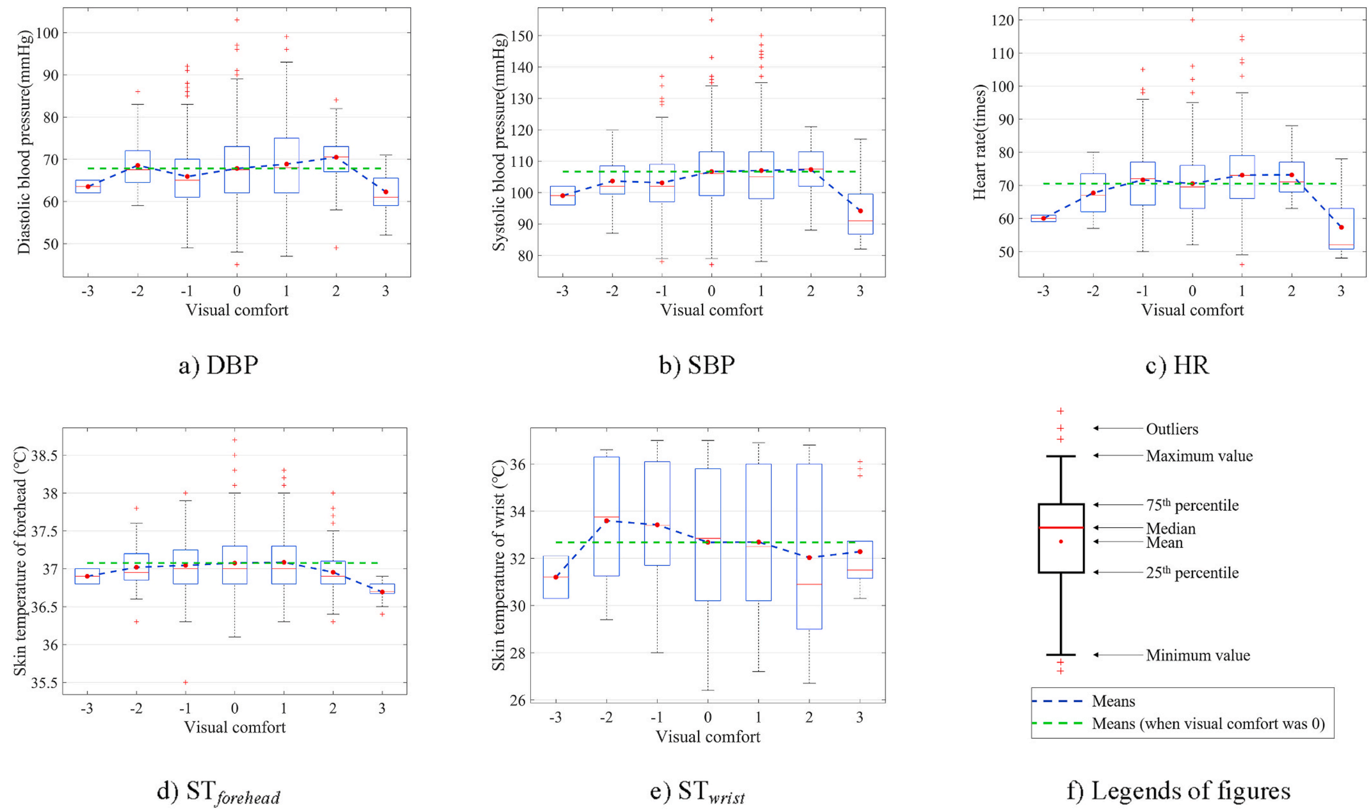


Fig. 12. Distributions of physiological parameters under different visual comfort.

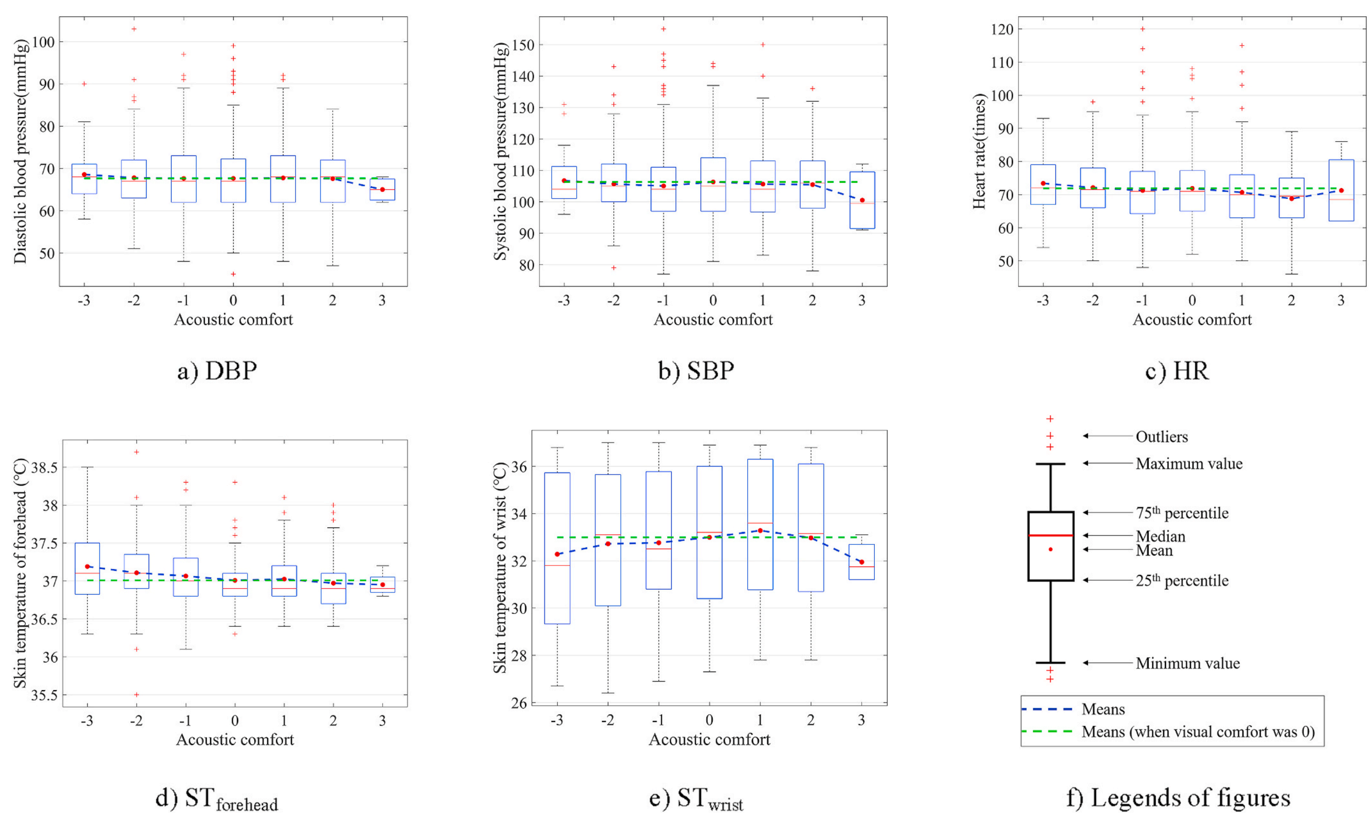


Fig. 13. Distributions of physiological parameters under different acoustic comfort.

Table 5
Result of factorial ANOVA of human comforts and physiological parameters (bold text when $P < 0.05$).

Source	Dependent Variable	Mean Square	F	P	η_p^2
Thermal comfort	SBP	1272.606	11.121	**.000**	.058
	DBP	363.582	5.483	**.000**	.029
	HR	1534.859	17.400	**.000**	.087
	ST_{wrist}	556.008	112.527	**.000**	.383
	$ST_{forehead}$	.903	7.079	**.000**	.038
Visual comfort	SBP	721.325	6.303	**.000**	.040
	DBP	293.027	4.419	**.000**	.028
	HR	404.644	4.587	**.000**	.029
	ST_{wrist}	10.576	2.140	**.047**	.014
	$ST_{forehead}$	.344	2.700	**.013**	.018
Acoustic comfort	SBP	74.210	.648	.691	.004
	DBP	9.552	.144	.990	.001
	HR	108.247	1.227	.290	.008
	ST_{wrist}	2.762	.559	.763	.004
	$ST_{forehead}$	.498	3.906	**.001**	.025

The numbers of subsets for the physiological parameters under different visual and acoustic comfort votes were all less than two, which indicates a statistically significant but negligible difference between different visual and acoustic comfort votes. In contrast the numbers of subsets for the physiological parameters under different thermal comfort votes were all greater than two, which indicates a stronger relationship between the thermal comfort votes and physiological parameters. In particular, the mean ST_{wrist} values under different thermal comfort votes, which were placed in four subsets, were clearly different.

Similarly, according to the number of subsets and the results mentioned above, the magnitudes of the differences in the physiological parameters under different human comfort votes were divided into three levels.

1) Obvious and regular difference (number of subsets = 4): the ST_{wrist} under different thermal comfort votes;
2) Moderate difference (number of subsets = 3): the HR and the $ST_{forehead}$ under different thermal comfort votes;
3) Slight difference (number of subsets < 3): the SBP, the DBP, the HR, the ST_{wrist} and the $ST_{forehead}$ under different visual comfort votes; the $ST_{forehead}$ under different acoustic comfort votes.

4. Discussion

4.1. Map of relationships

Fig. 14 summarizes the relationships among the environmental factors, human comfort votes, and physiological parameters based on the results given above. It shows that the physiological parameters are affected to varying degrees by multiple environmental factors and have different degrees of correlation with the human comfort votes. Specifically, except for SBP, each physiological parameter is affected by at least two physical environmental factors. Moreover, except for acoustic comfort, all the changes in measured physiological parameters under different thermal and visual comfort votes are statistically significant.

The magnitudes of the effects shown in Fig. 14 have complex meanings. We believe that the illuminance did not significantly affect the physiological/subjective outputs because the illuminance levels used for the experiment did not have a considerable impact on the activities or emotions of the participants, within a daily-life illuminance level range. In addition, the measured physiological parameters are also not directly related to the human visual system. The results also show that the illuminance has a moderately significant effect on the skin temperature of the wrist and the thermal perception of the participants, which is consistent with the results obtained by Giorgia Chinazzo et al. [23]. Moreover, because the human body has adaptability to the acoustic environment, the acoustic environment does not affect the physiological/subjective parameters significantly. After a period of 5 min of adaptation in our experiment, the human body had become accustomed to the environmental noise it was experiencing. In addition, this result may be related to the use of white noise as the sound source in this study. Research has concluded that white noise is able to mask environmental sounds and helps people focus, relax, and sleep. Therefore, the influence of the sound level on human comfort is not obvious. In terms of the significant influence of the environmental temperature on the measured skin temperatures, there are several reasons for the observed results. Humans produce their own heat through metabolism. This heat becomes an important part of how people perceive their thermal comfort. When the body temperature fluctuates, peripheral vasodilation or contraction is induced to regulate the body temperature. When the air temperature is low, to reduce heat dissipation, the blood flow to the skin decreases together with peripheral vasoconstriction. As a result, the skin temperature of the wrist should be lower than usual. In

Table 6
Means and post hoc Tukey HSD test results (that do not share a letter are significantly different; A < B < C < D < E).

Human comforts		N	SBP		DBP		HR		ST_{wrist}		$ST_{forehead}$	
Thermal comfort	−3	14	117.143	B	72.357	B	74.286	A, B, C	29.014	A	36.864	A, B
	−2	86	110.942	A, B	71.593	A, B	69.756	A	29.645	A, B	37.003	B, C
	−1	186	106.731	A	67.833	A, B	67.995	A, B	30.949	B	37.046	B, C
	0	470	104.045	A	67.117	A, B	71.787	A, B, C	33.46	C	37.109	C
	1	155	104.323	A	66.542	A	74.626	C	35.195	D	36.98	A, B, C
	2	15	110.933	A, B	69.6	A, B	73	B, C	35.687	D	36.747	A
	3	0										
	Subset		2		2		3		4		3	
Visual comfort	−3	2	99	A	63.5	A	60	B	31.2	A	36.9	A
	−2	36	103.667	A	68.528	A	67.694	B	33.594	A	37.019	A
	−1	236	103.085	A	65.881	A	71.64	B	33.421	A	37.044	A
	0	318	106.66	A	67.789	A	70.503	B	32.679	A	37.075	A
	1	267	107.011	A	68.831	A	73.067	B	32.692	A	37.085	A
	2	54	107.333	A	70.444	A	73.148	B	32.028	A	36.954	A
	3	13	94.154	A	62.231	A	57.308	A	32.285	A	36.692	A
	Subset		1		1		2		1		1	
Acoustic comfort	−3	39									37.19	A
	−2	204									37.107	A
	−1	307									37.064	A
	0	173									37.007	A
	1	129									37.024	A
	2	70									36.97	A
	3	4									36.95	A
	Subset										1	

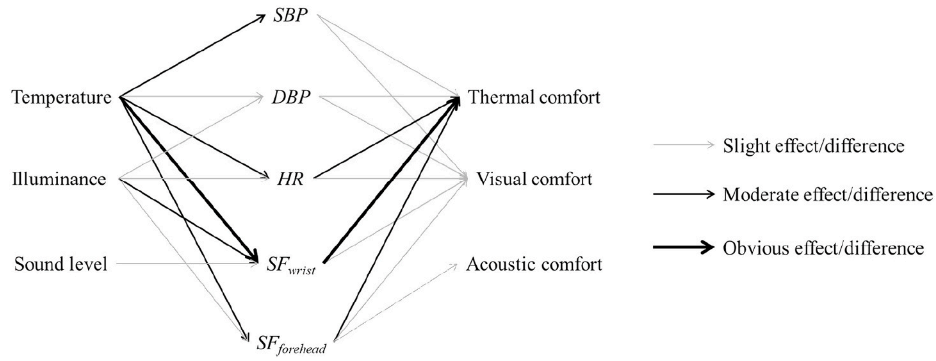


Fig. 14. Map of relationships between environmental factors, human comforts and physiological parameters.

contrast, when the temperature rises, blood vessels on the surface of the skin will dilate to increase heat dissipation, and the temperature at the wrist may be higher than usual.

Furthermore, human physiological parameters, especially skin temperatures, have significant potential to be used for estimating thermal comfort, which is also consistent with previous research results. Some previous studies associated thermal comfort with skin temperatures by developing mathematical human thermal models. Regression analyses and machine learning are usually adopted for these models. For example, as indicated in Table 7, Zhaojun Wang et al. [49] established quantitative relationships between thermal sensation and five local skin temperatures using linear regression. Wenjie Ji et al. [62] combined the thermal sensation with skin temperatures on the chest, upper arm, and lower limb using an iterative method. In addition, Joon-Ho Choi et al. [64] developed a classifier model, and Liu Shichao et al. [57] developed a mathematical human thermal model using local polynomial regression.

A comparison between the mathematical models in Table 7 shows that fewer local skin temperatures are associated in the models proposed by Joon-Ho Choi et al. [64] and Liu Shichao et al. [57]. It is understandable that the mathematical models with fewer local skin temperatures and high accuracy are desirable. Choi J H et al. [48] found that ST_{wrist} provided a stronger correlation with the temperature and thermal comfort than the other local temperatures (e.g., the forehead). Therefore, the quantitative relationships among the temperature, ST_{wrist}, and thermal comfort are further explored in this study.

4.2. *Quantified relationships between temperature, skin temperature of wrist and thermal comfort votes*

The local regressions in Fig. 15 show that ST_{wrist} increases linearly with the air temperature and exhibits an S-shaped relationship with the thermal comfort vote, which can be described using a logistic function. Furthermore, the quantitative relationship between the temperature (t) and ST_{wrist} and that between the thermal comfort vote (TC) and ST_{wrist} with a 95% confidence interval were established; these can be expressed as Equations (2) and (3), respectively.

$$ST_{wrist} = 0.66t + 17.88., \cdot R = 0.9815 \tag{2}$$

$$ST_{wrist} = \frac{6.97}{1 + e^{-1.48 \times TC - 0.62}} + 28.93, \cdot R = 0.9995 \tag{3}$$

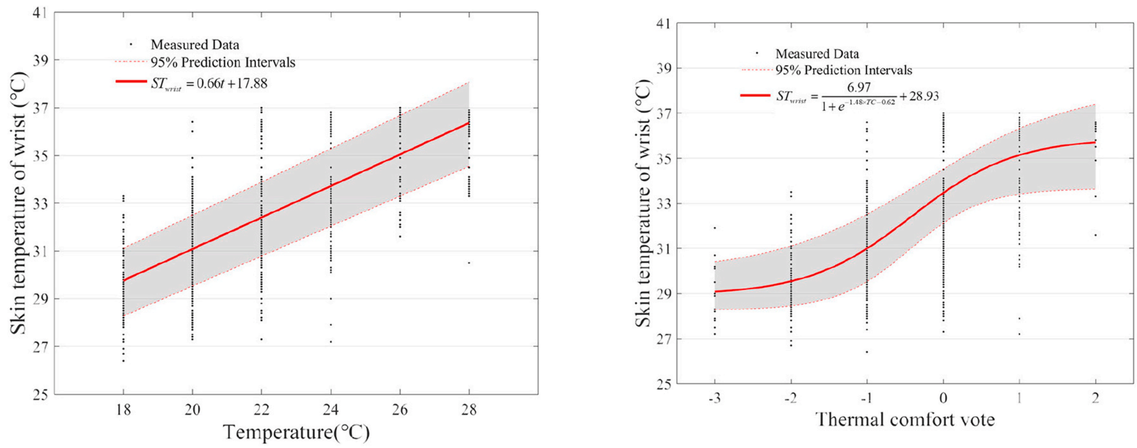
In Equations (2) and (3), ST_{wrist} is the temperature at the wrist (°C), t is the air temperature (°C), and TC is the thermal comfort vote on a 7-point numerical scale (ASHRAE thermal comfort scale).

These quantitative relationships were used to define the air temperature ranges considering typical thermal comfort, which can provide a guideline for effectively designing and operating indoor environments. Because Equation (2) is related to human factors, the air temperature ranges provided in this study are suitable for occupants with a metabolic rate of approximately 1.2 and clothing condition of approximately 0.75 clo.

Based on the thermal comfort model specified in ASHRAE Standard 55–2010 (i.e., the predicted mean vote, PMV), mechanical systems in numerous building systems have been operated by considering the thermal comfort vote to be between −0.5 and + 0.5, the acceptance rate of which is approximately 90%. When the PMV ranges from −1 to 1, the acceptance rate of occupants is around 80% [65]. Z. Deng and Q. Chen [72] also carried out a human subject experiment and established the acceptability of the indoor environment for different thermal comfort votes in offices using an artificial neural network (ANN). They found that when the thermal sensation experienced by the occupants was nearly neutral (from −0.5 to 0.5), the acceptance rate was 88%. When the thermal sensation was between slightly cool and slightly warm (from

Table 7
Mathematical human thermal models in some literatures.

Researches	Model	Number of local skin temperatures
Zhaojun Wang et al., 2013 [49]	$T_{skin} = 0.2T_{forehead} + 0.18T_{arm} + 0.50T_{back} + 0.05T_{hand} + 0.07T_{calf}$ $TSV = 0.6108T_{skin} - 20.155,\ R^2 = 0.9737$ Where T_{skin} is the mean skin temperature (∘C); $T_{forehead}$ is the skin temperature of the forehead (∘C); T_{arm} is the skin temperature of the arm (∘C); T_{back} is the skin temperature of the back (∘C); T_{calf} is the skin temperature of the calf (∘C); *TSV* is the ASHRAE 7-points thermal sensation vote;	5
Wenjie Ji et al., 2017 [62]	$T_{s-m} = 0.5T_{s-chest} + 0.14T_{s-upperarm} + 0.36T_{s-lowerlimb}$ $TSV = 1.45(T_{s-m} - T_{s-mpre}) - 0.16 + TSV_{pre}, R^2 = 0.76$ Where: $T_{s\text{-}m}$ is the mean skin temperature (∘C); $T_{s\text{-}chest}$ is the skin temperature of the chest (∘C); $T_{s\text{-}upperarm}$ is the skin temperature of the upper arm (∘C); $T_{s\text{-}lowerlimb}$ is the skin temperature of the lower limb (∘C); *TSV* is the ASHRAE 7-points thermal sensation vote; $T_{s\text{-}mpre}$ is the $T_{s\text{-}m}$ of the previous moment; TSV_{pre} is the *TSV* of the previous moment.	3
Joon-Ho Choi et al., 2019 [64]	Adopt J48 algorithm to generate a classifier model based on gender and the level of skin temperatures at the wrist back and forehead	2
Liu Shichao et al., 2019 [57]	Thermal sensation is correlated with the skin temperature at wrist or ankle by using local polynomial regressions (LOESS).	1



a) Relationships between ST_{wrist} and temperature b) Relationships between ST_{wrist} and thermal comfort votes

Fig. 15. Relationships between ST_{wrist} and temperature Relationships between ST_{wrist} and thermal comfort votes.

−1 to 1), the acceptance rate was 76%. To compare the acceptability of different thermal comfort votes in our study, we assumed that the thermal environment was acceptable for occupants when they felt satisfied or neutral, according to the 3-point numeric scale for human satisfaction presented in Fig. 6. The distribution of thermal satisfaction under different thermal comfort votes is shown in Fig. 16. The acceptance rate was approximately 90.3% when the occupants' thermal comfort was slightly warm, and the acceptance rate was approximately 73.5% when the occupants' thermal comfort was slightly cold, which indicates that the participants in our study preferred warmer conditions to colder conditions.

The air temperature ranges under different thermal comfort vote ranges are predicted using Equations (2) and (3). As shown in Fig. 17, when thermal comfort vote is neutral (equal to 0), the skin temperature at the wrist is 33.46 °C and the air temperature is 23.6 °C. When the thermal comfort vote is nearly neutral (from −0.5 to 0.5), the air temperature ranges from 21.71 °C to 25.076 °C. In addition, when thermal comfort vote is between slightly cool and slightly warm (from −1 to 1), the air temperature ranges from 19.8 °C to 26.23 °C.

Table 8 lists and compares the air temperature ranges obtained in different studies. In this table, Z. Deng et al. [72] predict the air temperature ranges by an artificial neural network (ANN) model and ASHRAE [65] uses PMV model. As can be seen, the air temperature ranges obtained in this study are essentially consistent with those obtained in other studies, which are slightly wider. One possible reason is that the acceptance in our study was smaller than that in other studies, particularly when the thermal sensation was slightly cool (73.5%). Another possible reason is that the data in this study were gathered primarily from students, who were young and 77% of whom were male; the age and gender of the participants may have caused biases in the results.

The analysis above established quantitative relationships between

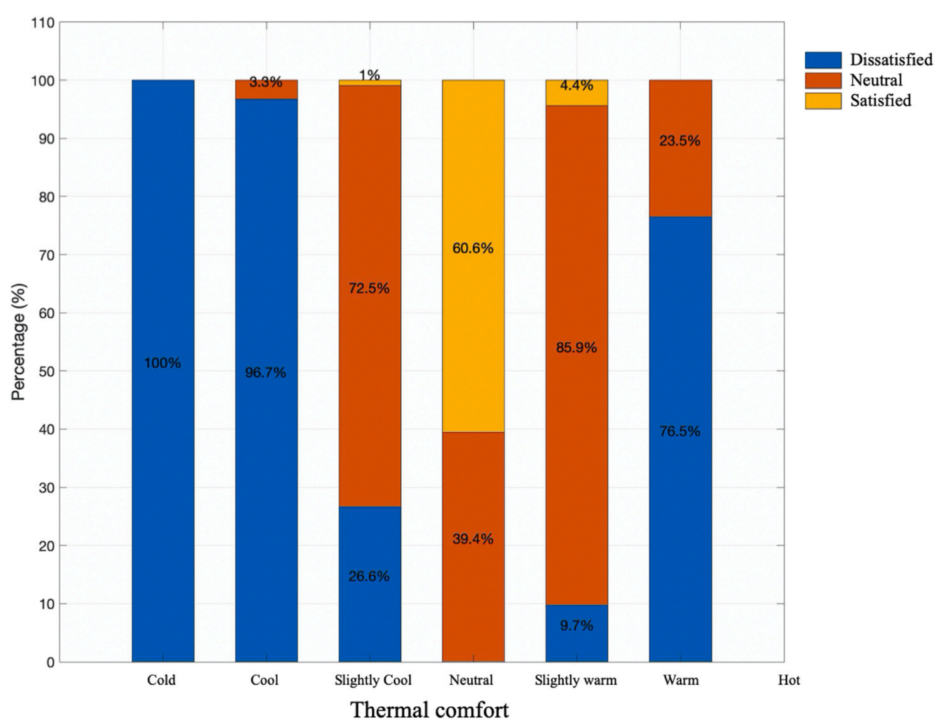


Fig. 16. Relationships between ST_{wrist} and temperature, ST_{wrist} and thermal comfort votes (The solid curves are local regression fit with 95% confidence interval (shaded areas)).

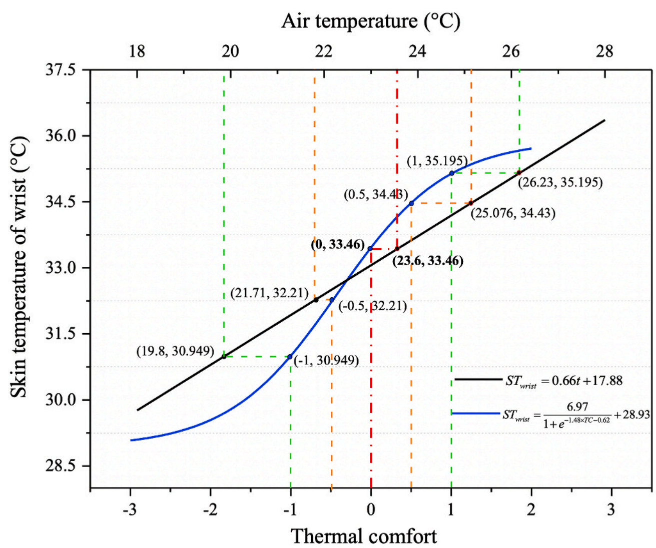


Fig. 17. Distribution of thermal satisfaction under different thermal Relationships among air temperature, skin temperature of wrist and thermal comfort.

the air temperature and ST_{wrist} and the thermal comfort vote and ST_{wrist}. The results suggest the possibility of using the skin temperature at the wrist as a variable that indicate thermal comfort. In addition, relevant quantitative relationships were established. With the development of intelligent wearable devices, such as wristband devices [60], there is increased application potential to use the skin temperature at the wrist to provide real-time distributions of physiological parameters under different environmental operation conditions without consideration of the human factors of individual occupants.

Table 8
Comparison of air temperature ranges under different thermal comfort ranges.

Thermal comfort ranges	[-1, 1]			[-0.5, 0.5]		
Studies	Our study	Z. Deng et al.	ASHRAE 55	Our study	Z. Deng et al.	ASHRAE 55
Air temperature range (°C)	[19.8, 26.23]	[20.6, 25.6]	[20, 26]	[21.71, 25.076]	[21.2, 24.2]	[23.6, 26.8]
Acceptance	73.5%–90.3%	76%	80%	-	88%	90%

5. Conclusion

This study investigated the relationships between the temperature, illuminance, and sound level and typical physiological parameters (systolic blood pressure, diastolic blood pressure, heart rate, skin temperature of wrist and head) and human perceptions by conducting a climate chamber experiment with $6 \times 6 \times 4 = 144$ (temperature $\times$ illuminance intensity $\times$ sound level) controlled indoor environment conditions. The main results are summarized as follows:

1) The distributions of physiological parameters under different environmental factors revealed that ST_{wrist} varied linearly with the air temperature. Whether, which, and how physiological parameters were affected by environmental factors were investigated and determined. The magnitudes of the effects were divided into three levels. In particular, ST_{wrist} was obviously affected by the air temperature.
2) The different degrees of correlation between physiological parameters and human comfort were identified. This analysis found that the ST_{wrist} values for different thermal comfort vote groups and visual comfort vote groups were significantly different, which indicates that ST_{wrist} was most consistent with the thermal comfort (having an *S*-shaped relationship) and has significant potential to be used as an index of thermal comfort.
3) Quantitative relationships between the air temperature and ST_{wrist} and between the thermal comfort vote and ST_{wrist} were established. The air temperature ranges corresponding to occupant thermal comfort votes of neutral (equal to 0), nearly neutral (from −0.5 to 0.5), and between slightly cool and slightly warm (from −1 to 1) were then predicted, which were in good agreement with previous research and ASHRAE.

This research's findings are meaningful in that the results showed varying degrees of effect of multiple environmental factors to physiological parameters and different degree of correlation between physiological parameters and human comfort. Nevertheless, there are still a few limitations. A sample size by considering a larger difference of gender and age need to be considered for further studies. And a deeper analyze, to investigate the combined effect (especially interaction effect) of multiple environmental factors on physiological parameter, multiple physiological parameters on human individual comfort, should be carried out in the future. Moreover, the results presented are relies on statistical significance exclusively for interpretation, whether they have practical importance still need to be further confirmed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2020.107193.

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