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Thermal comfort under radiant asymmetries of floor cooling system in 2 h and 8 h exposure durations

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ABSTRACT

Radiant heating and cooling systems inherently exhibit radiant asymmetries. Although many researchers have investigated the thermal comfort effects of asymmetric radiant environments, the exposure duration has not been emphasized, especially under floor heating and cooling scenarios. In this study, we conducted a series of tests in a climate chamber with floor cooling radiant asymmetries with human participants to investigate their thermal comfort effects from short-term (2 h) and long-term (8 h) exposure perspectives. The 2 h exposure test indicates that the floor cooling systems cause discomfort complaints more easily than other radiant systems such as ceiling heating/cooling because of its stronger cooling effects on the lower body parts. The cold floor resulted in significantly colder local thermal sensations and lower local skin temperatures in the foot, calf, and thigh areas. The comparison between the 2 h and 8 h exposures suggests that exposure duration affects both the subjective and physiological thermal comfort responses significantly. Further, 2.5~4 hours are required for the foot and calf temperatures to stabilize in radiant floor cooling asymmetry cases. In accordance with these laboratory tests, we proposed two radiant asymmetry-satisfaction curves and equations for the floor cooling system with consideration of exposure duration. The calculated temperature limits for typical floor cooling room are >18.5 ºC at a 2 h exposure and >20.5 ºC at an 8 h exposure. These curves and temperature limits can serve as a reference for future guidelines for floor cooling system design and operation.

KEYWORDS

radiant systems; radiant heating and cooling; asymmetric radiation; exposure duration

NOMENCLATURE

BMI	body mass index
PD	percentage of dissatisfaction
Ref.	reference case
SD	standard deviation
TCV	thermal comfort vote
TSV	thermal sensation vote
T_{sk}	skin temperature (ºC)

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https://escholarship.org/uc/item/8h49f5vr

VRT	vector radiant temperature (ºC)
Δt_{pr}	radiant temperature asymmetry (ºC)

1. INTRODUCTION

With the advantages of energy conservation, and space and noise reduction, radiant heating and cooling systems have gradually garnered market attention in many eastern Asian and European countries [1] and are being considered as promising alternatives to conventional air-conditioning systems. Compared to other relatively uniform thermal environments, radiant systems are typically accompanied with radiant asymmetries, vertically, horizontally, or both. This difference raises a question as to whether such radiant asymmetries will affect the occupants' thermal comfort, or are they the same with uniformly distributed thermal environments? This question is important for the application of radiant systems and has been listed as top-ten unsolved question [2]. A review study by Karmann et al. [3] indicated that despite many theoretical benefits, such as reduced air movement [4, 5], less draft risk [6] and smaller air temperature gradient [7], radiant systems are not more thermally comfortable. Because an increasing number of buildings tend to use radiant heating/cooling systems and with the emergence of new radiant system types [8], the thermal comfort effects of radiant asymmetries should be considered when designing and operating those systems.

Unlike uniform thermal environments where the contribution of radiant temperature on comfort can be considered approximately equal to that of the air temperature, in radiant asymmetries, the geometry and shape of the local body parts can affect the relative importance of radiation and convection significantly [9, 10]. To define their radiant heat exchange with the surrounding environment, indexes such as the Vector Radiant Temperature (VRT) and Radiant Temperature Asymmetry (Δt_{pr}) had been proposed by McIntyre [11] and Fanger [9]. For example, the widely used Δt_{pr} represents the asymmetry of a radiant field by referring to the difference between the plane radiant temperature of the two opposite sides of a small plane element. Typically, the plane element is 0.6 m above the floor, which is the height of the 'center' of a seated person.

The impacts of asymmetric radiation on thermal comfort had been investigated extensively through human subject tests in the late 1970s [9, 12]. Their studies included the heated/cooled ceilings and heated/cooled walls radiant asymmetries. Subsequently, Olesen et al. tested the thermal comfort effects of the radiant asymmetry of spot cooling (a cold vertical panel with dimensions 1m × 2m, 0 ºC) [13] and investigated the influences of clothing, activity level, and air movement [14]. In addition, other efforts have been conducted to investigate the asymmetric radiation limits. For example, Chrenko [15] investigated the discomfort caused by a heated ceiling as early as 1953. McIntyre and Griffiths [16, 17] studied the thermal comfort effects of overhead thermal radiation in the early 1970s. More detailed information about these studies can be found in a technical report by Huizenga et al. [18]. Based on these studies, some specific equations and curves (presented in Figure 14 and Table 7) have been proposed to describe the relationships between asymmetric temperature and percentage of subjective dissatisfaction [9, 12], which were subsequently compiled in standards such as ISO 7730 [19] and ASHRAE 55 [20] to guide the design of radiant systems. Table 1 lists some of the allowable radiant temperature asymmetry limitations from the ASHRAE 55 standard.

Table 1 Allowable radiant temperature asymmetry [20]

Radiant temperature asymmetry (Δt_{pr}) °C			
Warm ceiling	Cool ceiling	Warm wall	Cool wall
<5	<14	<10	<23

More recently, other efforts have been conducted to understand the heat transfer interactions between radiant asymmetries and the human body. For example, Sakoi et al [21] studied thermal comfort, skin temperature, and sensible heat loss distribution in various asymmetric radiant fields. They found that the relationship between local skin temperature and local sensible heat loss varies with environmental thermal non-uniformity. Wang et al [22] investigated human thermal response in asymmetrical cold radiation environments and found the overall thermal sensation and mean skin temperature exhibited a linear relationship. Ferenc et al. [23] studied the impact of elevated air velocity and airflow directions on subjective thermal comfort sensation under asymmetric radiation. By reviewing these papers, we found that two problems still require further investigations.

The first concern is regarding the different types of radiant asymmetries. With the emergence of new application scenarios such as floor cooling [24] and floor heating [25], their corresponding requirements and guidelines have been absent. To the best of our knowledge, neither asymmetry-satisfaction curves nor equations has been developed for floor heating/cooling systems. Floor heating/cooling usually has different comfort effects on human body when compared to ceiling heating/cooling, because the former system has stronger effects on lower body part while the latter has stronger effects on upper body part. As the lower and upper body parts have different weighting factors when determining whole-body thermal comfort, the radiant asymmetry limit for floor and ceiling radiant systems might be different. The current floor surface temperature requirements (see Table 2) are based on the comfortable contacting temperature because it is believed that either an excessively cold or excessively hot floor will lead to local thermal discomfort complaints [26, 27, 28]. Whether the current temperature limits are in accordance with the asymmetric-satisfaction requirement still requires further investigation.

Table 2 Surface mean temperature limits for radiant systems (ASHRAE 55 [20], EN 15377-1 [29] and JGJ142 [30])

Surface	Standard	Cooling	Heating
Ceiling	ASHRAE 55	based on radiant asymmetry and comfort	based on radiant asymmetry and comfort
	EN 15377-1	based on radiant asymmetry and comfort	based on radiant asymmetry and comfort
	JGJ142	≥ 17 °C	No limit, but recommend ≤ 36 °C
Floor	ASHRAE 55 (Table 5.2.44)	≥ 19 °C	≤ 29 °C
	EN 15377-1	Sedentary ≥ 20 °C Higher activity ≥ 18 °C	Occupied zone ≤ 29 °C Peripheral zone ≤ 35 °C
	JGJ142	≥ 19 °C	≤ 29 °C

The other concern is regarding exposure duration. As most previous studies only tested for short-term exposures, typically 1-2 h, one may ask if the occupants were exposed to radiant asymmetries for a longer period, such as 8 h, as in typical office hours, will the corresponding requirements and temperature limits be the same or different? In the literature, we found only one study that mentioned different exposure durations. Olesen [27] designed a study with two different time-scales to search for the comfortable floor temperature for bare feet and non-barred feet. The bare feet test lasted 10 min and the feet with shoe test lasted for 3 h. He found that the floor material affected the bare feet exposure significantly, while it was insignificant for the with-shoes exposure. Unfortunately, Olesen's study was not deliberately designed to examine the impacts of exposure duration. More efforts are required to discuss this issue.

Based on the two uncertainties above, the primary objective of our study is to understand the thermal comfort effects of different radiant asymmetries especially from the view of different exposure durations. Based on a series of climate chamber human subject tests, we propose practical guidelines such as asymmetry-satisfaction curves and temperature limits for the future design and operation of radiant floor systems.

2. METHODS

2.1. Experimental facility

The tests in this study were conducted in a climate chamber at Tongji University. As shown in Figure 1, the chamber is a sleeve structure composed of an interior and exterior compartment, consisting of a radiant plate water system and three air systems. The air system contains the internal air system, interlayer air system, and an independent fresh air system. The chamber measures in 4.2 m × 3.6 m × 2.4 m, with a 2 m × 1 m window on the south wall. The ground, top and inner walls of the three sides were laid with metal radiating plates.

During the experiment, the ceiling, side walls, and floor temperature were controlled by the radiant panel system with an accuracy of 0.5 ºC. Considering the influence of wall emissivity during the radiation heat transfer process between the wall and human body, we pasted white paper on the metal surface of the surrounding and on the floor, and the emissivity is 0.9. The chamber air temperature and relative humidity were controlled by independent electric heater and humidifies. Fresh air was processed by the cooling air handling unit and an electric reheater, and was supplied from grille diffusers with a volume flow rate 180 m^3/h. The large airflow rate was to reduce temperature stratification in the chamber so that to exclude the comfort effects of stratification. The chamber can control the air temperature and relative humidity to within ± 0.5 ºC and ± 5% precision respectively, and the background air speed can be lower than 0.15 m/s.

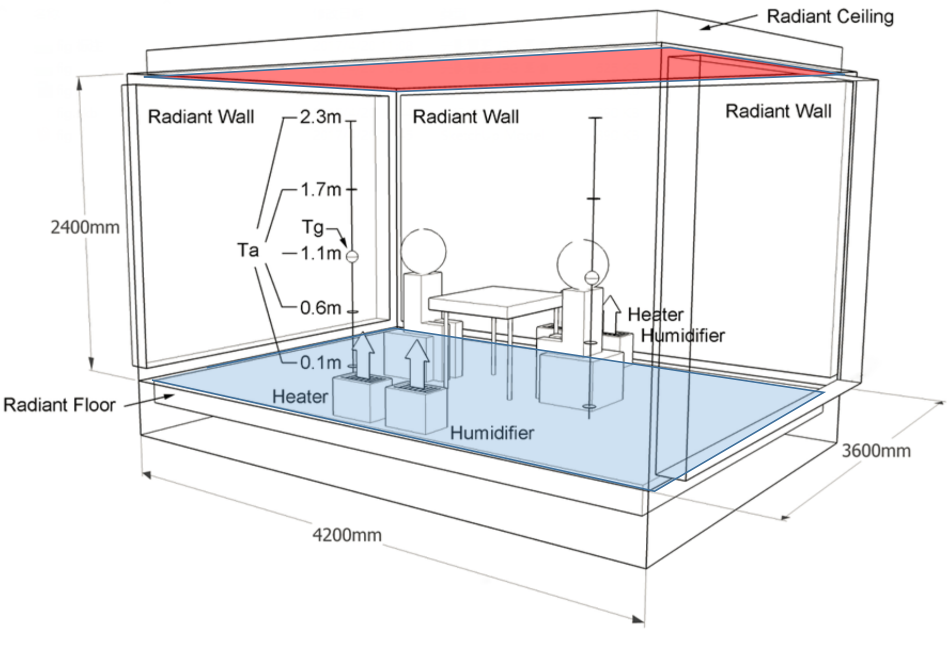

Figure 1 Schematic diagram of the climate chamber. Note, in the center of the floor, there is a static pressure box in size of 2.4m × 1.2m beneath the floor. During the test, we sealed the underfloor supply air outlets and let cold air circulate in static pressure box to ensure its upper surface temperature was controlled in line with the designed floor surface temperature. To some extent, the static pressure box can be regarded as a radiant panel conditioned by cold air supply. As the box didn't affect the uniformity of floor surface temperature, we didn't draw it in the diagram.

2.2. *Experiment design*

Test plan. The overall study was separated into two phases. The first phase consists of 2 h tests aiming to compare the impacts of different radiant asymmetries. The second phase consists of 8 h tests aiming to investigate the impacts of exposure duration. To choose the proper test conditions, the Predicted Mean Vote (PMV) of each test case was calculated in advance. The selection of test cases followed three principles: 1) Each case should represent a radiant asymmetry; 2) All the cases should have the same ambient temperature and mean radiant temperature; 3) All the cases should have the same overall thermal condition with a PMV of 0. Through these measures, we ensured that all the test cases had different radiant asymmetric temperatures, but their overall thermal environments were controlled at similar levels.

The 2 h test cases are listed in Table 3. Five thermally neutral cases with different asymmetric radiations and radiant surface temperatures were selected. Among them, Cases 1, 2, 4, and 5 were designed to simulate the asymmetric radiant scenarios, while Case 3 was the reference case with uniform symmetrical radiation. Based on the 2 h test results, we selected the floor cooling case to further study the exposure duration issues. The 8 h test cases are also listed in Table 3. We created four different asymmetric radiation temperatures ranging from 13 to 0 °C. Among them, case 4 was the reference case with a uniform thermal environment.

When selecting test conditions, we included some extreme cases, such as case 1 in 2h exposure with floor temperatures of 36°C and 12ºC. The purpose is to study thermal comfort responses under a wider range of conditions so that help to identify a suitable radiant asymmetry range for real applications. To make sure the test conditions be close to real situations, we strictly controlled the overall thermal conditions with PMV≈0 by adjusting other surface temperatures. Furthermore, to include real application conditions, case 2 and case 3 in 2h exposure, case 3 and case 4 in 8h exposure were designed in line with current radiant system design standards.

Table 3 Test conditions

Test case		Description	Air temperature T_a (ºC)	Relative humidity RH (%)	Mean radiant temperature T_r (ºC)	Operative temperature T_{op} (ºC)	Ceiling temperature $T_{ceiling}$ (ºC)	Floor temperature T_{floor} (ºC)	Asymmetric radiant temperature Δt_{pr} (ºC)
2h test	1	Cold floor and hot ceiling	25.5 ± 0.5	50 ± 5	25.5 ± 0.5	25.5 ± 0.5	38	12 (note)	19.7
	2	Cool floor and warm ceiling					32	18	10.4
	3 (Ref.)	Uniform surface temperature					25.5	25.5	0
	4	Warm floor and cool ceiling					18	32	-10.5 (note)
	5	Hot floor and cold ceiling					14	36	-16.6 (note)

		Description	Air temperature T_a (°C)	Relative humidity RH (%)	Mean radiant temperature T_r (°C)	Operative temperature T_{op} (°C)	Other wall temperatures T_{wall} (°C)	Floor temperature T_{floor} (°C)	Asymmetric radiant temperature Δt_{pr} (°C)
8h test	1	Floor cooling	25.5 ± 0.5	50 ± 5	25.5 ± 0.5	25.5 ± 0.5	27.0	12 (note)	13.7
	2	Floor cooling					26.5	16	9.6
	3	Floor cooling					26.0	19	6.4
	4 (Ref.)	Uniform surface temperature					25.5	25.5	0.0

(Note, the negative sign of the asymmetric radiant temperature describes only the direction. The asymmetric radiant temperatures were calculated based on room geometry and view factors. A more detailed description has been attached in Appendix A. In case 1 of the 2 h exposure, the floor temperature of 12 °C was lower than the dew point temperature; therefore, condensation occured during the test. We asked the subjects to ignore the condensation and accelerated its evaporation after the test.)

Test procedure. Figure 2 presents the 2 h and 8 h experimental procedures separately. The 2 h tests contained four steps. First, the subjects were given 15 min to calm down, change clothes and wear skin temperature sensors in the preparing phase. Subsequently, all the subjects were given 30 min to adapt themselves to the chamber environment and learn how to vote in the adapting phase. Further, the subjects experienced a 60 min formal test period. The final 15 min was designed to end the whole test. The voting frequencies and skin temperature recoding frequency are shown in Figure 2. The 8 h study was performed similarly. It first consisted of 2 h for adaptation, followed by a 1 h voting period. After that, subjects had 1 h lunch time to eat food in the chamber, followed by another 4 h voting period.

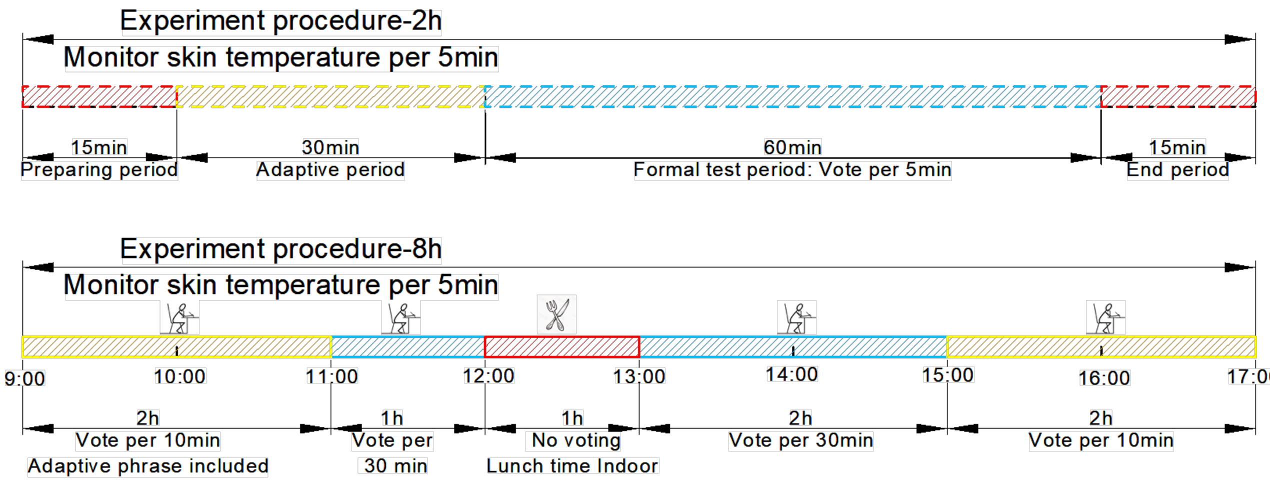

Figure 2 Experiment procedure

Subjects. We attempted to recruit the same subjects for all the tests, but because the 2 h and 8 h tests were conducted at different times, two groups of subjects were used. Their profiles are presented separately in Table 4. In total, 24 female and 24 male subjects were selected to participate in the experiments. They were all college students studying in Shanghai, China for at least 3 months prior to the test. They had light-to-none caffeine or alcohol consumption and smoking habits – less than 1 cup of coffee or 2 cigarettes a day, and normal exercise intensity – 2-4 times per week.

Table 4 Subject profile

Group	Gender	Sample size	Age (year)	Height (cm)	Weight (kg)
2 h test	Male	16	18.5±0.6	174.2±3	65.7±3.5
	Female	16	18.8±0.6	165.3±2	53.6±2.5
	Average	——	18.7	169.8	59.7
8 h test	Male	8	22.7±0.5	174.3±2.5	65.2±3
	Female	8	22.4±0.5	165.4±3	59.5±2.5
	Average	——	22.5	169.9	62.4

2.3. Subjective questionnaire and physiological measurement

During the test, all the subjects were required to engage in sedentary activities with a metabolic rate of approximately 1.1 met and the wore a standard uniform that simulated a light clothing ensemble (cotton shirt, cotton long trousers, cotton undershorts and cotton shoes with 1-cm thickness of polyurethane material on the sole) with an insulation value of 0.6 clo. Further, the subjects were asked to answer subjective questions on their overall whole-body thermal comfort perception and local-body parts sensation. 9 body parts (head, chest, abdomen, back, arm, palm, thigh, calf, and foot) were chosen to record the local thermal perceptions. The questionnaire included a thermal sensation vote (TSV), thermal comfort vote (TCV), satisfaction vote and other miscellaneous information. The scales of these votes are as shown in Table 5. They are in accordance with the scales of the ASHRAE standard [20] and those in the global thermal comfort database [31].

Table 5 Subjective vote scale.

Scale	TSV	TCV	Satisfaction vote
3	Hot	---	Very satisfied
2	Warm	---	Satisfied
1	Slightly warm	---	Just satisfied
0	Neutral	Comfortable	---
-1	Slightly Cool	Just uncomfortable	Just dissatisfied
-2	Cool	Uncomfortable	Dissatisfied
-3	Cold	Very uncomfortable	Very dissatisfied

In addition to the subjective questionnaires, each subject's skin temperature was collected using T type thermocouple. The sensors were attached at the aforementioned nine body areas. Subsequently, the mean skin temperature was calculated using the following equation [32]:

$$T_{sk} = 0.07T_{forehead} + 0.18T_{chest} + 0.18T_{back} + 0.07T_{forearm} + 0.07T_{upper\ arm} + 0.05T_{hand\ back} + 0.19T_{thigh} + 0.13T_{calf} + 0.06T_{foot} \qquad \text{Equation 1}$$

2.4. Data processing

For a better comparison among the different subject groups, descriptive statistics such as mean and standard deviation were calculated. The voting sample distribution was compared with the normal distribution through the Kolmogorov-

Smirnov one-sample test. It shows that the subjective votes were in accordance with normal distribution. The significance of group differences was verified through paired T-tests assuming equal variances. The T-test outcomes were interpreted as follows: $p \leq 0.001$ means highly significant, $0.001 < p \leq 0.01$ means significant, $0.01 < p \leq 0.05$ means weakly significant, and $p > 0.05$ means not significant. Statistical significance was accepted when $p \leq 0.05$.

To determine the time duration for the human body to reach a stable status, we first performed a preliminary assessment by observing how the mean voting values changed with time, and subsequently adopted the "sliding interval intragroup variance analysis" method. Specifically, we defined a "sliding interval" length n (representing the vote number, in this study, n = 5) starting from the first vote. After that, we performed variance analysis among the voting values in the interval. Further, we discarded the first vote in the interval, added the following $(n+1)^{th}$ vote, and reperformed the intragroup variance analysis, until the "sliding interval" was applied for all the rest votes. If the variance analysis showed no statistical significance, we considered no difference in the group; otherwise, we accepted a significant difference. The experiment data were prepared and organized in Excel 2013. All statistical analyses were performed using R 3.5.1. The figures and charts were created using R 3.5.1 and Origin 8 in accordance with the calculated thermal comfort responses.

3. RESULTS

3.1. 2 h exposure tests

3.1.1. Whole-body thermal comfort response.

Figure 3 shows how the whole-body thermal sensation ($TSV_{overall}$) and thermal comfort ($TCV_{overall}$) changed with voting time in different test cases. Generally, $TSV_{overall}$ and $TCV_{overall}$ exhibit a decreasing trend, especially for the first several votes at the beginning. This means that even after a 30-min adaptation, the subjects still required more time to reach the stable thermal status. Through variance analysis, the length of the stabilizing period was marked in grey in Figure 3. Typically, the participants' subjective thermal comfort perceptions ($TSV_{overall}$ and $TCV_{overall}$) can be stabilized after 35 min. Hence, the following analysis of whole-body sensations only considered the last five votes of each test case.

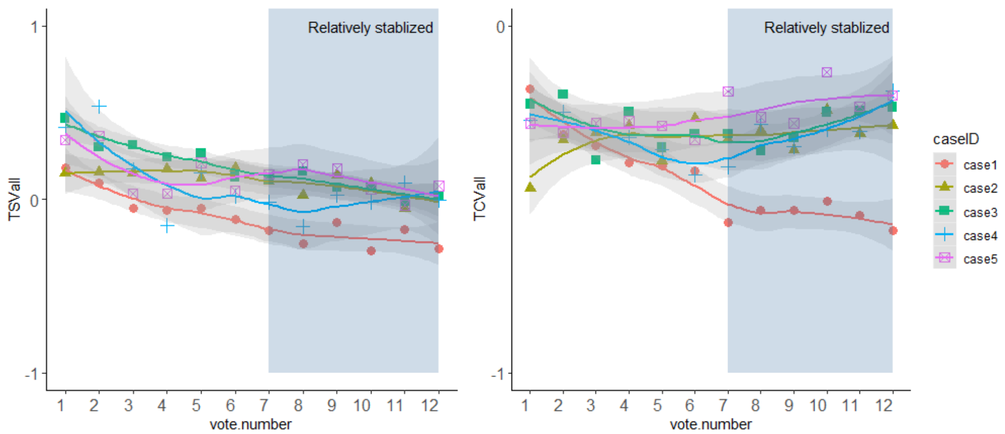

Figure 3 Variation in the whole-body thermal perceptions. Note, the shaded 'relatively stabilized' period was determined by variance analysis described in section 2.4. Normally, subjects' thermal comfort perceptions tended to be stabilized after 35min. Therefore, we used the last 5 votes of each 2h test case to do further analysis. But, we can't not conclude that $TSV_{overall}$ or $TCV_{overall}$ has been fully stabilized during the 2h test.

Figure 4 compares each test case's stabilized whole-body thermal sensation and thermal comfort. When comparing with the reference case (Case 3), the paired T-test results only support significantly lower $TSV_{overall}$ and worse $TCV_{overall}$ in case 1 (with $p < 0.05$, as marked in Figure 4), while other three cases exhibited quite similar thermal comfort evaluations with the reference case (with $p > 0.05$). For thermal sensation comparison, Case 1 had a slightly cooler thermal sensation with $TSV_{overall}$ approximately -0.2 while the other four cases had neutral $TSV_{overall}$ of approximately 0.1.

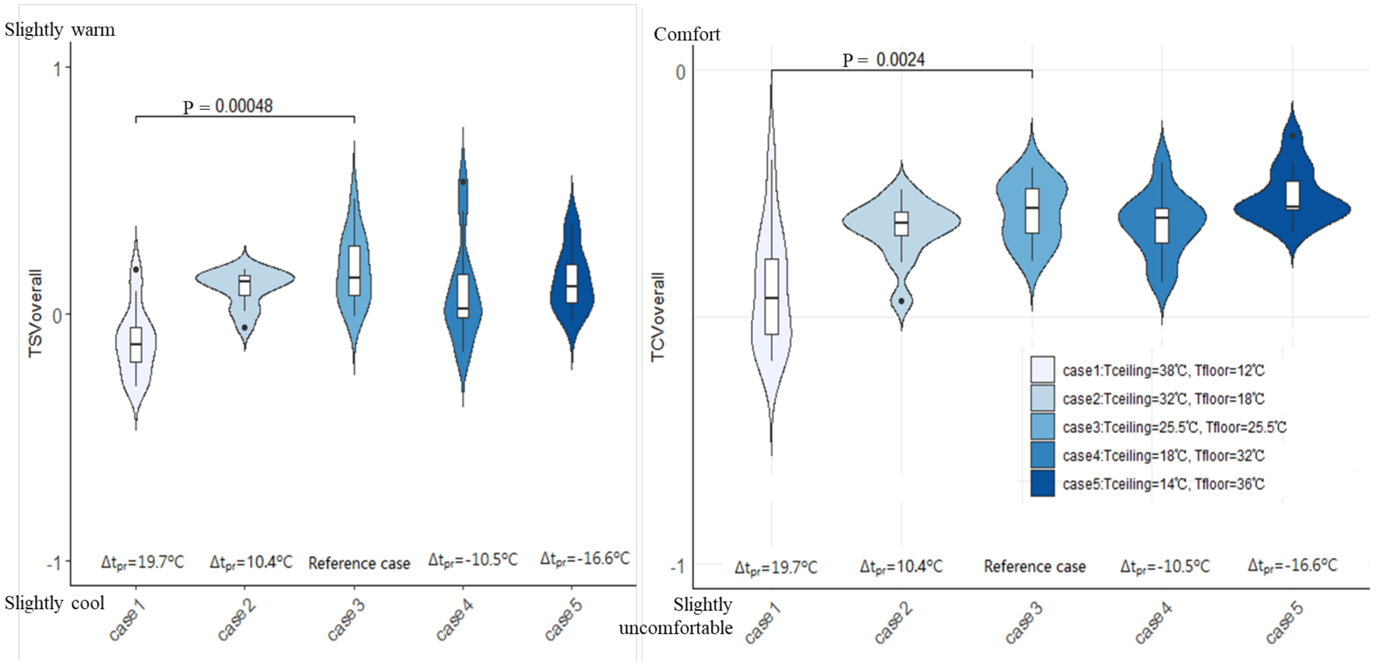

Figure 4 Whole-body thermal perceptions of 2 h test cases. Note: the box plot shows data distribution including minimum, first quartile, median, third quartile, and maximum. The violin shape represents a rotated kernel density plot on each side.

3.1.2. Local thermal comfort response.

Case 1 (Δt_{pr} = 19.7 °C) is used as an example in Figure 5, showing the changes in local thermal comfort (TCV_{local}) of each body part during the test period. These TCV_{local} changing lines can be clustered into two groups. The TCV_{local} of lower body parts such as the thigh, calf, and foot decreased significantly at the beginning and subsequently stabilized at approximately -1.0 in the last 7 votes. Other body parts had much smaller TCV_{local} drops, and primarily maintained in the range of 0 - -0.4. It appears that the cold floor temperature affected the lower body parts' thermal comfort perception more significantly.

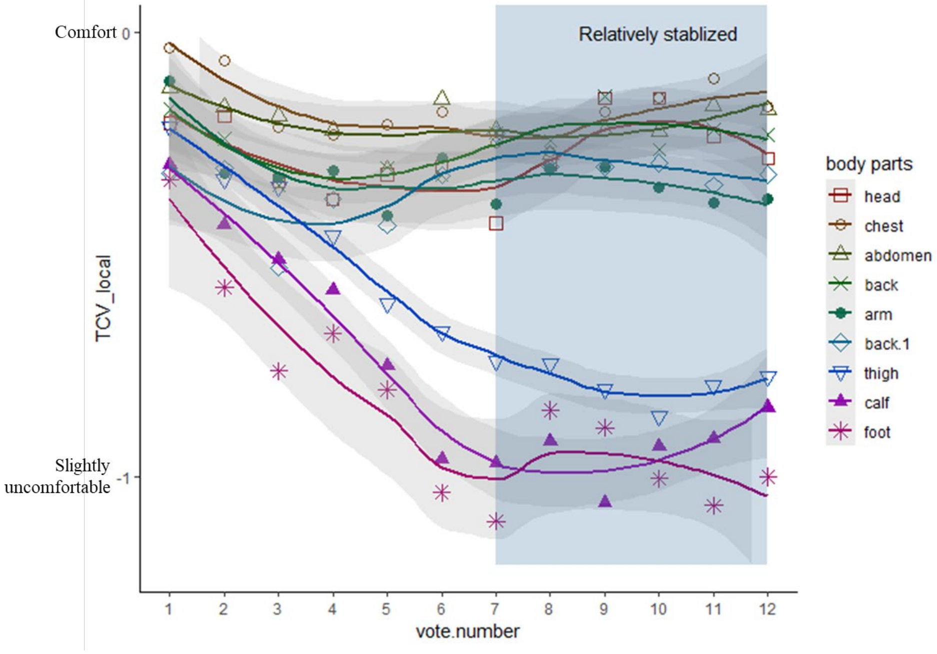

Figure 5 Variation in the local body part thermal perception of 2 h exposure for Case 1

To compare the local thermal sensation under different radiant asymmetries, Figure 6 compares the TSV_{local} of Cases 1, 2, 4, 5 with that of case 3. Much information can be interpreted from this figure. First, the local thermal sensations in uniform thermal environment (e.g., case 3) show that the back, arm, and lower body parts exhibited lower TSV_{local}, while the trunk and head had higher TSV_{local}. Next, the cold floor and hot ceiling cases (e.g., Case 1) had similar TSV_{local} in the upper body parts with Case 3 ($p > 0.05$), but much colder TSV_{local} in the lower body parts, especially for the foot, calf, and thigh ($p < 0.001$). Subsequently, although the asymmetric radiant temperature of the cool floor and warm ceiling case (e.g., Case 2) is as high as 10.4 ºC, Case 2 exhibits quite similar TSV_{local} with Case 3 ($p > 0.05$). Next, both the warm floor case (e.g., Case 4) and hot floor case (e.g., Case 5) had significantly warmer TSV_{local} in the lower body parts such as foot and calf ($p < 0.01$). However, the cool or cold ceilings in these two cases did not lead to colder TSV_{local} in the upper body parts. These results suggest that the cold floor radiant asymmetry had a stronger influence on the local thermal perception than the warm ceiling radiant asymmetry.

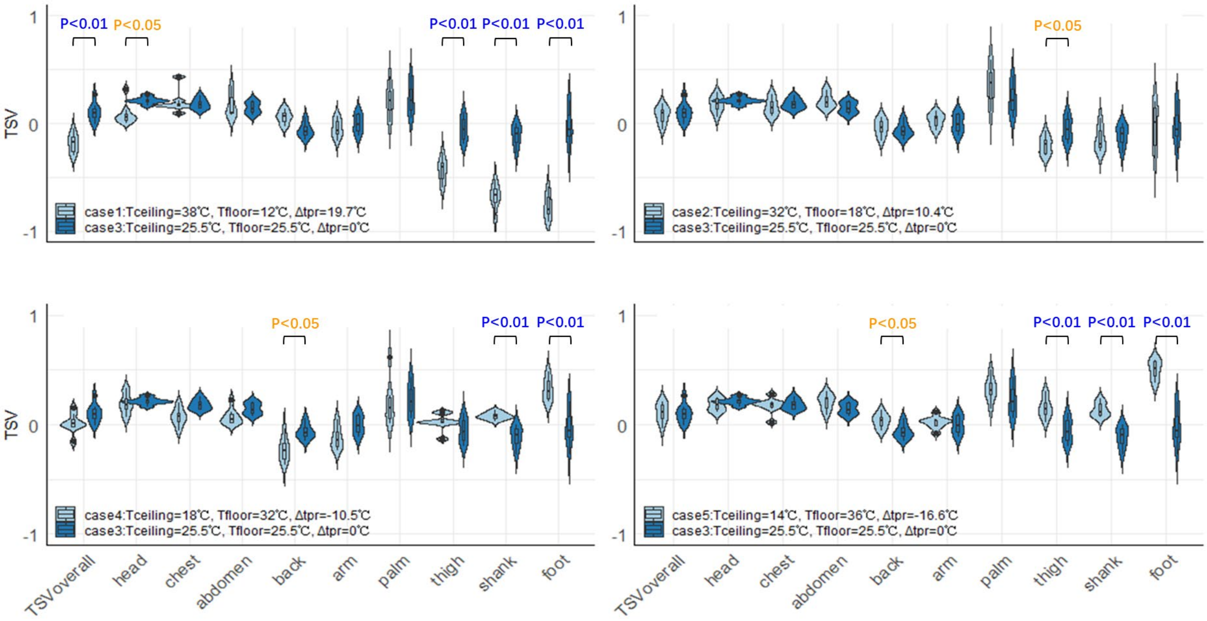

Figure 6 Local thermal sensation comparison of different 2 h test cases

To understand the reason behind the TSV_{local} differences shown in Figure 6, Figure 7 compares the local skin temperatures of Cases 1, 2, 4, 5 with that of Case 3. The cold floor can primarily affect the local skin temperature in lower body parts such as the foot and shank areas. As shown in Figure 7, Case 1 and Case 2 had significantly lower skin temperature in the lower body parts such as the foot, calf, and thigh than the reference case ($p < 0.001$). This might be why the cold floor scenarios were reported to be colder and less comfortable. For the warm floor cold ceiling scenarios such as Case 4 and Case 5, the skin temperature in the head and trunk parts were lower.

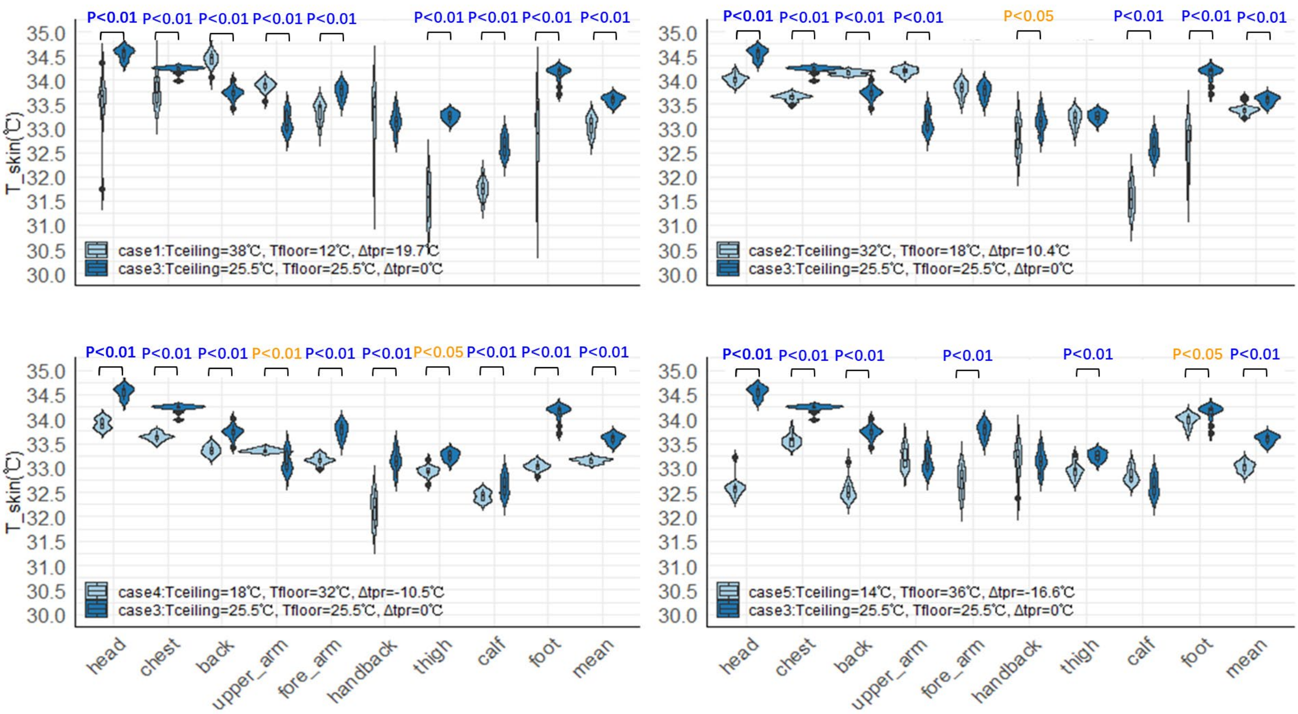

Figure 7 Local skin temperature comparison of different 2 h test cases

To investigate the effects of exposure durations, Case 1 is used as an example in Figure 8, showing the local skin temperature changes with exposure time under the cold floor and hot ceiling scenarios. The local skin temperatures of the calf and foot decreased continuously; however, even by the end of the test, they did not reach a stable state. This phenomenon raises a question: will the short-term exposure experiment underestimate the discomfort effects of radiant asymmetries? Assuming that the lower skin temperature corresponds to colder thermal sensation, it is highly possible to underestimate the radiant asymmetry discomfort in the 2 h short-term exposure experiments. Therefore, we continued with another series of tests by extending the exposure duration to 8 hours. Moreover, as the 2 h tests showed significant differences in whole-body thermal perception under the cold floor scenario, we selected the cold floor radiant asymmetry to perform further explorations.

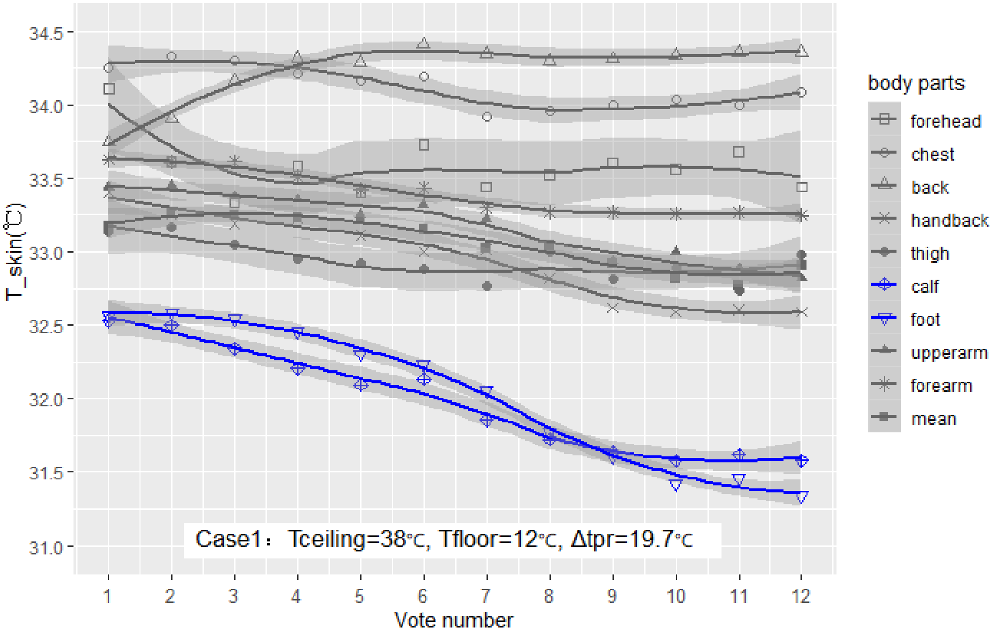

Figure 8 Local skin temperature changes in 2 h test (Case 1)

3.2. 8h exposure tests

3.2.1. Whole-body thermal comfort response

Similar to Figure 4, Figure 9 compares the 8 h test cases' whole-body thermal sensation and thermal comfort during the stabilized stage. Compared to the reference case, the paired T-tests suggest significant a significantly lower $TSV_{overall}$ and worse $TCV_{overall}$ in all the asymmetric radiant cases (p < 0.01). In addition, decreasing trends are observed with the increased radiant asymmetries. The larger the radiant asymmetry, the lower is the $TSV_{overall}$, and the worse is the $TCV_{overall}$.

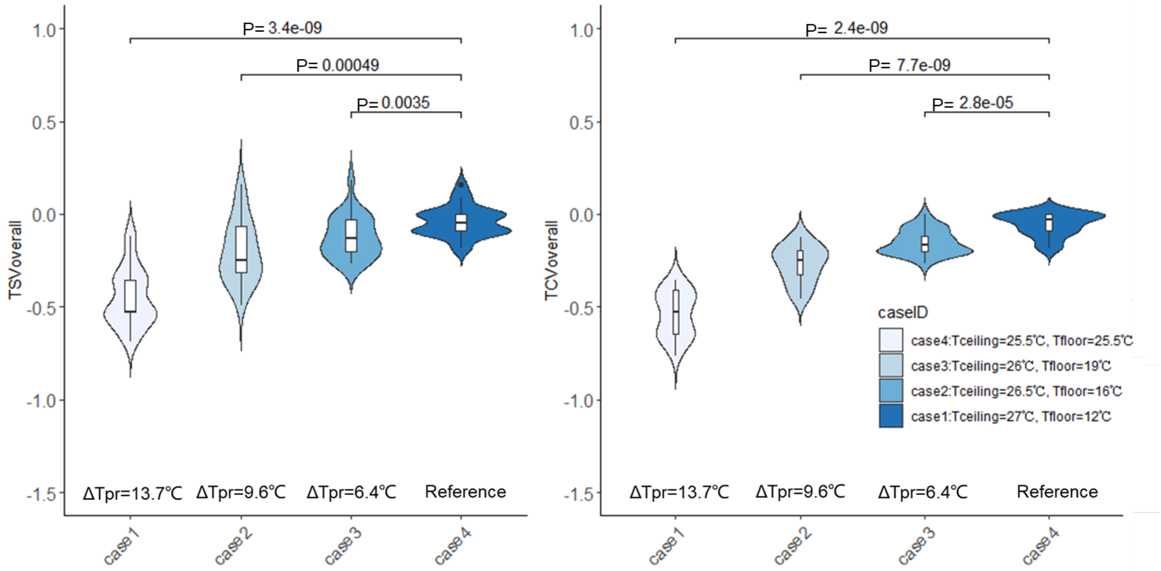

Figure 9 Whole-body thermal perceptions of 8h test cases

3.2.2. *Local thermal comfort response*

To determine the stabilizing time of skin temperature under different radiant asymmetries, Figure 10 tracks the local skin temperature changes in the 8 h tests. In the uniformly conditioned Case 4, the skin temperature can reach a stable state in half an hour. However, the cold floor scenarios such as Case 1 need more than 4 h to become stabilized. Further the cool floor scenarios such as Case 2 and Case 3 take 2.5 - 3 hours to become stable. The lower the floor temperature, the longer is the time needed to reach a stable state. This phenomenon proved the importance of extending the exposure duration.

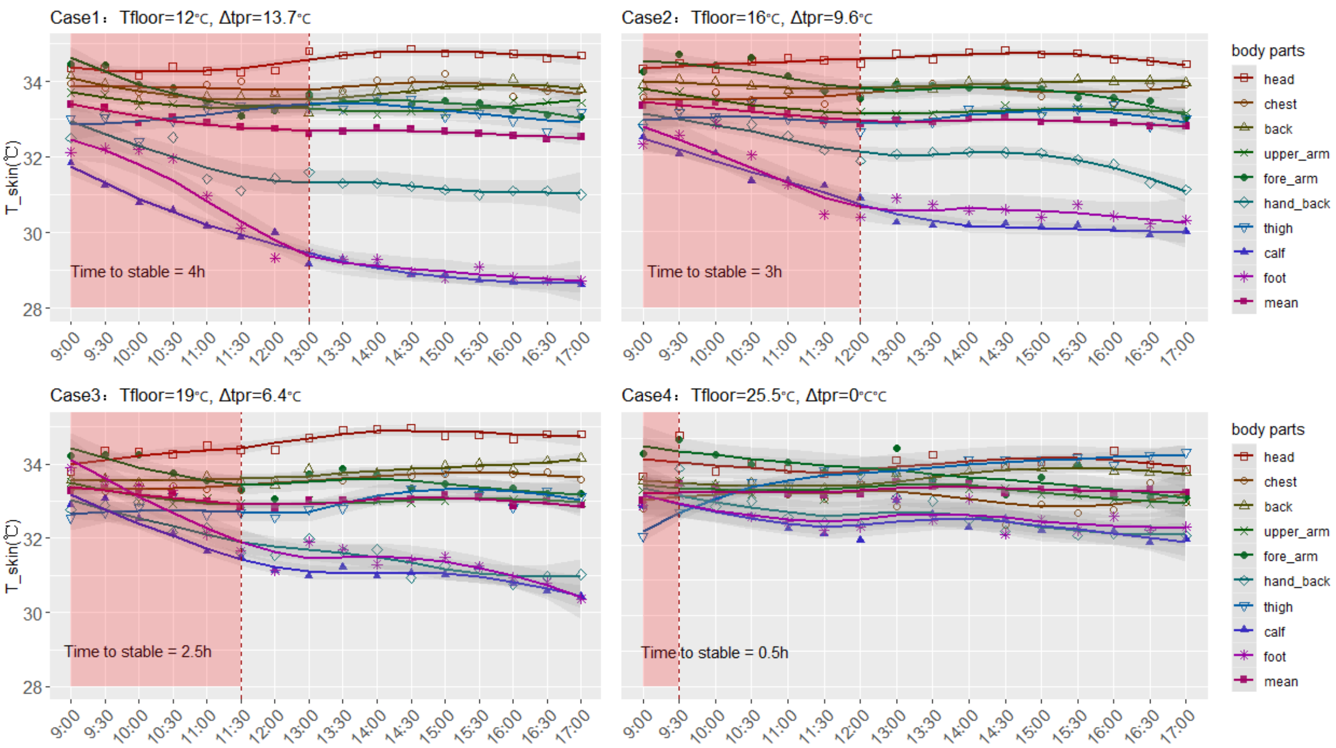

Figure 10 Local skin temperature changes of the 8 h tests

3.2.3. Short-term(2h) and long-term(8h) exposure comparison

Figure 11 compares each of the 8 h test case's first two hours and the last two hours' thermal sensation and thermal comfort. Statistical analyses suggest that exposure duration has no significant influence on the uniformly conditioned Case 4 ($p > 0.05$) but affects the asymmetric radiant cases significantly ($p < 0.01$). The longer exposure duration results in lower thermal sensation and worsens the thermal comfort perception (as shown in Case 1 and Case 2). Additionally, Figure 11 shows that the larger the Δt_{pr}, the stronger is the influence of the exposure duration.

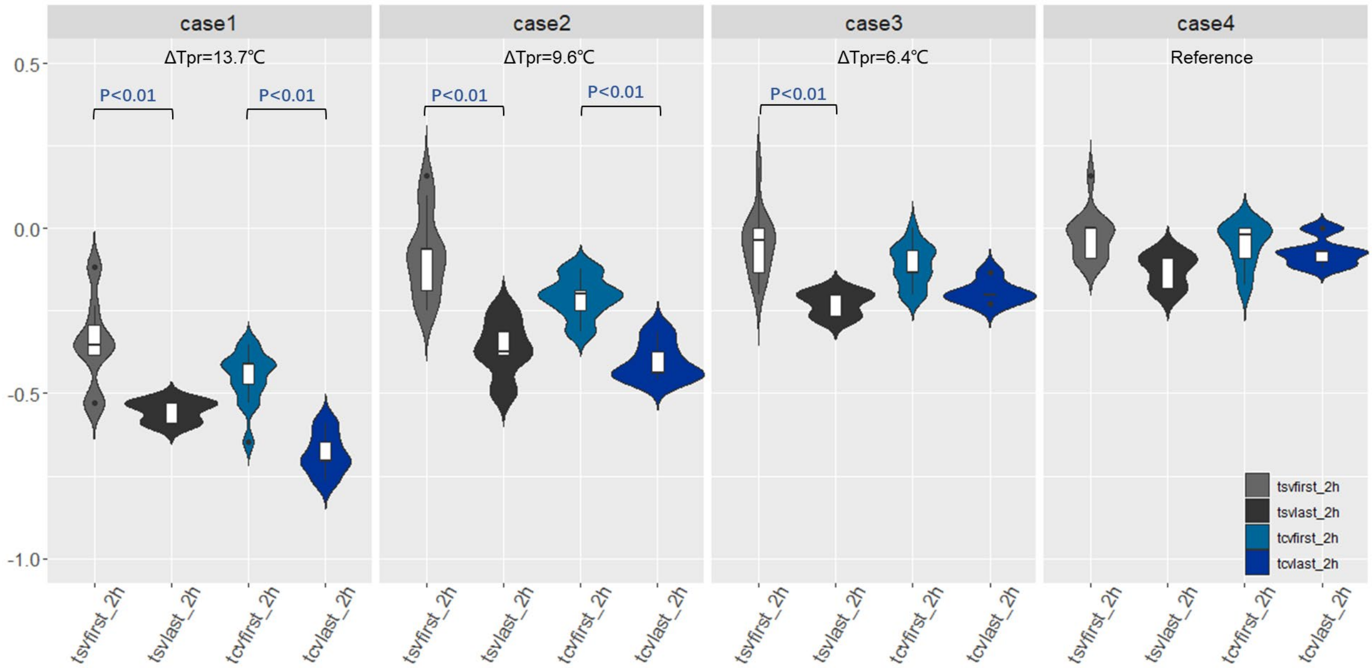

Figure 11 Whole-body thermal comfort comparison between 2 h and 8 h exposures. The "2 h" results were from the first two hours in the 8 h tests and the "8 h" results were from the last two hours.

For the comparison of local thermal comfort between the 2 h and 8 h exposures, Figure 12 takes the local skin temperature as an example. It compares the local skin temperatures from the first two hours and the last two hours of the 8 h tests. No significant difference in local skin temperature was observed between the 2 h and 8 h exposure durations in the uniformly conditioned case (Case 4). However, significant differences were shown in the other cold floor scenarios. In Case 1, 2, and 3, the skin temperatures of the hand back, lower leg, and foot in the last 2 h of exposure were significantly lower than those in the first 2 h.

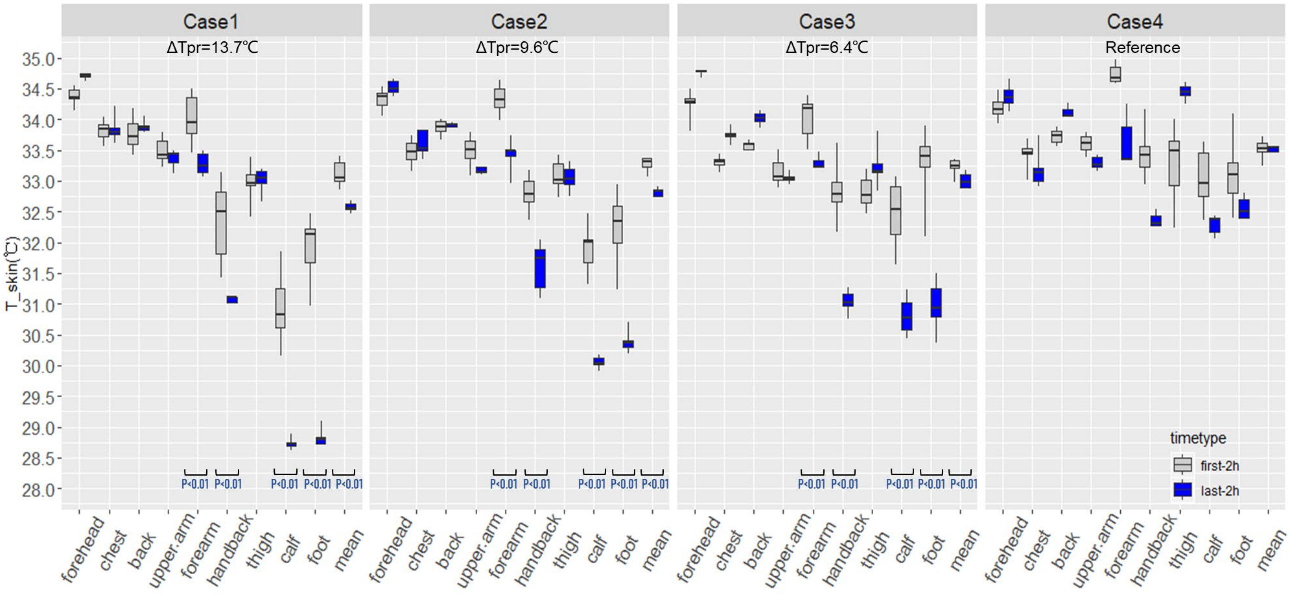

Figure 12 Skin temperature comparison between 2 h and 8 h exposures.

4. DISCUSSION

4.1. More discomfort complaints regarding cold floor

In the 2 h exposure test, Case 3 was designed to simulate a uniform radiant environment, and other cases were supposed to simulate radiant asymmetries resembling floor heating, floor cooling, ceiling cooling, ceiling heating, and some of their combinations. All these cases were thermally neutral conditions with an air temperature of 25.5 ºC with a mean radiant temperature of 25.5 ºC (see Table 3). The subjective thermal comfort responses shown in Figure 4 suggests that subjects expressed a preference for the floor heating cases (Case 4 and Case 5) while the floor cooling (Case 1 and Case 2) were reported as less comfortable, especially when the floor surface temperature was reduced to 12 ºC as in Case 1.

The cold floor temperature in Case 1 and 2 led to significant colder local thermal sensations and lower skin temperatures in the lower body parts like the foot, calf, and thigh (see Figures 7 and 8). Unlike the ceiling that is far away from the occupants' upper body, the floor surface typically directly contacts or is extremely very close to lower body parts such as the foot and buttock (when people sit on the floor) [33]. This will enhance the heat interaction between these body parts and the floor, leading to a stronger thermal effect.

Figure 13 shows the correlation analyses between the subjects' whole-body thermal sensation and their local body parts sensation. It indicates that subjects' whole-body thermal sensation is closely related to the lower body parts' thermal sensation. The correlation coefficient between $TSV_{overall}$ and TSV_{foot} is as high as 0.88, much higher than that between $TSV_{overall}$ and TSV_{head}. Further, a 'dominant effect' exists in the correlation coefficient matrix (see Figure 13), where the arm has an overall comfort correlation coefficient of 0.8 while that of the hand is only 0.33. Several previous studies have reported the similar observation – the overall thermal sensation or thermal comfort perception was typically dominated by the most un-neutral or uncomfortable local body parts. For example, discomfort from a cold foot/hand would dictate a whole-body cold discomfort while hot complaints for the head and back/seat are critical for comfort in warm environments [34, 35]. These two observations may partially explain why the floor cooling scenarios were perceived colder and less comfortable, because the flooring cooling typically exhibits stronger cold effects on the lower body extremities such as the foot and calf.

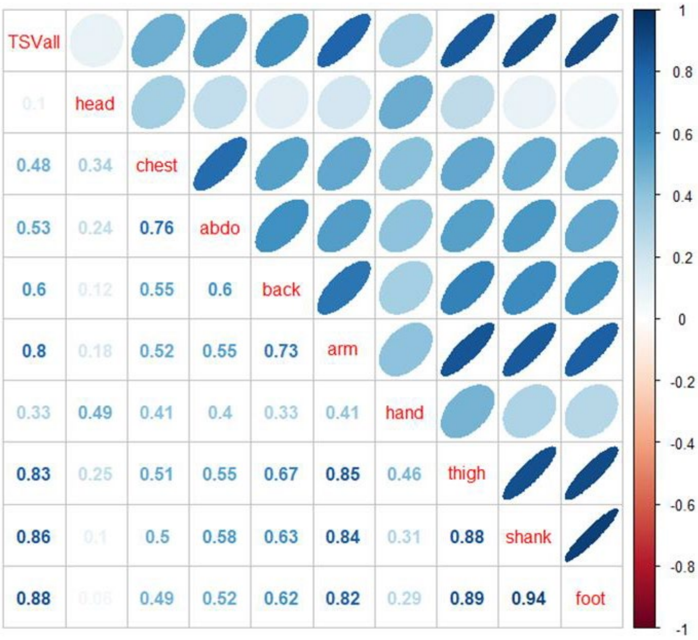

Figure 13 The correlations between local and overall thermal sensations

4.2. Comfort effects of exposure duration

To investigate how exposure duration influences the subjects' thermal comfort response, we compared the 2 h and 8 h test results. As shown in Figures 11 and 12, these comparisons suggest that exposure duration can affect subjects' thermal comfort perception significantly. The skin temperature comparison presented in Figure 10 indicates that the skin temperatures of the lower body parts only required 0.5 hours to become stable in the uniformly conditioned case, however, the floor cooling cases required more than 2.5 ~ 4 hours to be stabilized.

Based on the observations, we developed two radiant asymmetry-satisfaction curves and equations for floor cooling system with the consideration of exposure duration, see Figure 14 and Table 7**.** Although our experimental design was not the same as that of Fanger's [12], we followed his method to develop the curves and equations for the floor cooling. First, we calculated subjects' thermal dissatisfaction rate (PD) with equation 2 under the three tested radiant asymmetries for 2 h and 8 h exposures, reperately (as shown in Table 6). Next, we applied the regression fitting method to determine the A, B, and C constants in equation 3. Subsequently, we constructed the radiant asymmetry-satisfaction curves, as shown in Figure 14.

$$PD = \frac{Dissatisfied\ votes}{Total\ votes} \times 100\% \qquad \text{Equation 2}$$

$$PD = \frac{100}{1+\exp(A-B\cdot\Delta t_{pr})} - C \qquad \text{Equation 3}$$

Table 6 Percentage of dissatisfaction (PD) in 2 h and 8 h exposures

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https://escholarship.org/uc/item/8h49f5vr

Asymmetrical radiation temperature ΔT_{pr} (°C)	2 h exposure PD (%)	8 h exposure PD (%)
13.7±0.5	57.1	59.6
9.6±0.5	19.5	38.3
6.4±0.4	5.1	9.8
0.1±0.1	0.0	0.0

(Note: the dissatisfied votes include the votes of 'Just dissatisfied', 'Dissatisfied', and 'Very dissatisfied'.)

The results show that the floor cooling typically exhibits higher dissatisfaction rate under the same asymmetric radiant temperature than the other radiant systems. Further, the 8 h exposure curve is steeper than the short-term 2 h exposure curve, indicating that prolonged exposure time in radiant asymmetry would lower the satisfaction rate. Table 7 lists the detailed equation and radiant asymmetry limits for different radiant scenarios.

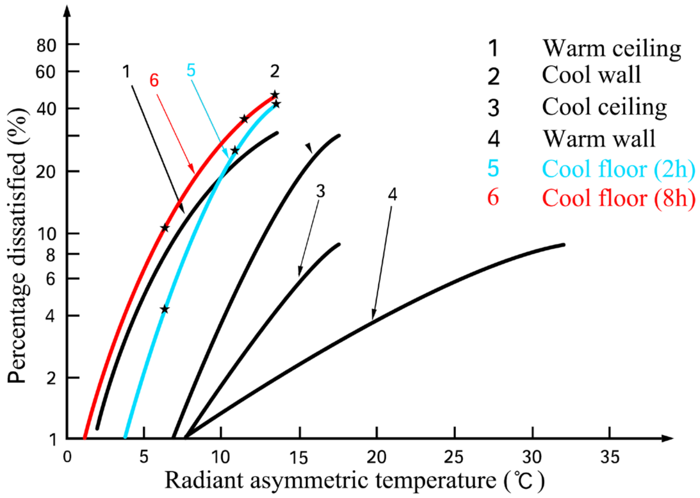

Figure 14 Radiant asymmetry-satisfaction curves for different radiant systems (the black lines were excerpted from [12], the red and blue lines were based on the current study's uncomfortable complaint rate)

Table 7 Radiant asymmetry-satisfaction equations

Radiant systems	Equations	Radiant asymmetry limit
Warm ceiling [12]	$PD=\frac{100}{1+\exp(2.84-0.174\cdot\Delta t_{pr})}-5.5$	Δt_{pr}<23 °C
Cool wall [12]	$PD=\frac{100}{1+\exp(6.61-0.345\cdot\Delta t_{pr})}$	Δt_{pr}<15 °C
Cool ceiling [12]	$PD=\frac{100}{1+\exp(9.93-0.50\cdot\Delta t_{pr})}$	Δt_{pr}<15 °C
Warm wall [12]	$PD=\frac{100}{1+\exp(3.72-0.052\cdot\Delta t_{pr})}-3.5$	Δt_{pr}<35 °C
Cool floor (2h)	$PD=\frac{100}{1+\exp(4.19-0.327\cdot\Delta t_{pr})}-5.8$, R^2=0.97	Δt_{pr}<15 °C

Cool floor (8h)	$PD = \frac{100}{1+\exp(3.33-0.271\cdot\Delta t_{pr})} - 4.7$, R^2=0.98	Δt_{pr}<15°C

In addition to radiant asymmetry, floor surface temperature is another factor that must be considered when designing or operating radiant floor cooling system. Take a typical office room of dimensions 4.2 m × 3.6 m × 3.5 m (L × W × H) as an example. First, the Δtpr limits were determined in accordance with Figure 14 and the limit of 5% dissatisfaction rate, which were Δtpr ⩽ 6.4 °C for the 2 h exposure and Δtpr ⩽ 4.1 °C for the 8 h exposure. Next, we assumed that other walls and the ceiling exhibited uniform surface temperatures of 25 °C [20, 29]. Subsequently, the floor cooling surface temperature can be calculated in accordance with the Δtpr limits and view factor calculations. For the 2 h exposure, the floor cooling surface temperature should be higher than 18.5°C; for the 8 h exposure, the surface temperature should be higher than 20.5°C. The current standard recommended the floor cooling surface temperature is 19 °C [20, 29, 30], which is between the two values calculated from the radiant asymmetry limits.

4.3. Limitation and future challenge

This study investigated the comfort effects of floor cooling radiant asymmetry and different exposure durations. However, several uncertainties and future challenges should be mentioned. First, this study primarily focused on the floor cooling case; in future study, the radiant floor heating system should also be included. Next, the occupants' actual exposure in real buildings may be different from the chamber experiment, especially when considering the clothing patterns and moving-around behaviors.

5. CONCLUSION

This study investigated the thermal comfort responses under floor cooling radiant asymmetries in 2 h and 8 h exposure durations through human subject tests. The following findings and suggestions are worthy to noteworthy:

1) The 2 h tests indicated that different radiant asymmetries may lead to different subjective and physiological thermal comfort responses. Compared to other radiant systems, the radiant floor cooling caused discomfort complaints easier because of the significantly colder local thermal sensations and lower local skin temperatures in the foot, calf, and thigh areas.

2) The exposure time in the radiant floor cooling affected the subjects' thermal comfort perception and skin temperature response significantly. The comparison between the 2 h and 8 h tests indicated that the prolonged exposure time would worsen the whole-body and foot area thermal comfort evaluations. The time required to reach a stable skin temperature in the radiant asymmetries would be longer than that in the uniform thermal environment. For example, only 0.5 h was required for the foot temperature to become stable in the uniformly conditioned case, while more than 4 h were required for the floor cooling case to become stabilized.

3) Two radiant asymmetry-satisfaction curves and equations were developed for the radiant floor cooling system with the consideration of exposure duration. Radiant floor cooling typically exhibits higher dissatisfaction rate under the same asymmetric radiant temperature than other radiant systems. The long-term (8 h) exposure curve is steeper than the short-term (2 h) curve, indicating that prolonged exposure time in radiant asymmetry would lower the satisfaction rate.

4) In a typical 4.2 m × 3.6 m × 3.5 m office room, the calculated temperature limits for floor cooling are >18.5 °C for a 2 h exposure and >20.5 °C for an 8h exposure. Although the current standard recommended floor cooling surface

temperature of 19 °C was based on a comfortable contacting temperature, it was quite consistent with the calculated limits of radiant asymmetry.

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