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Publication Date
2022-10-01

Data Availability
The data associated with this publication are available upon request.

Peer reviewed

Experimental evaluation of thermal comfort, SBS symptoms and physiological responses in a radiant ceiling cooling environment under temperature step-changes

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 https://doi.org/10.1016/j.buildenv.2022.109512,

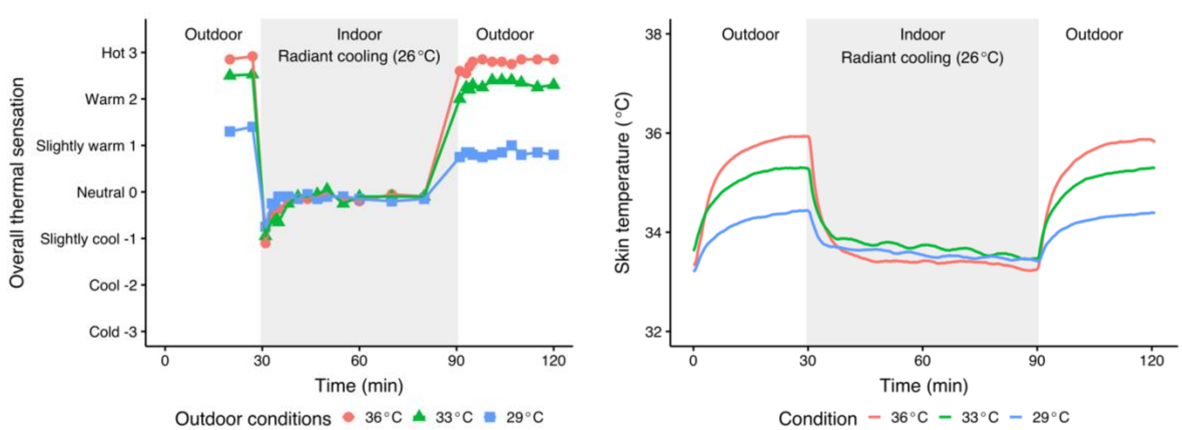
Highlights

1. We investigated human responses to temperature step-changes in a radiantly cooled space.
2. We showed physiological parameters changed significantly under temperature step-changes.
3. We found researchers need to wait at least 30 min to stabilize a human subject.
4. We observed thermal sensation overshoot under temperature down-step.

Abstract

People usually experience transient thermal environments when entering or leaving a conditioned indoor environment. This has been previously explored but there is little knowledge on the impact of temperature step-changes on thermal comfort in a radiantly cooled environment. We aim to investigate human comfort and underlying physiological mechanism in such conditions. We assessed thermal comfort, sick building syndromes (SBS) symptoms, and physiological responses. Twenty healthy participants were exposed to three temperature step-change conditions with three outdoor air temperatures (29 ℃, 33 ℃ and 36 ℃) and one indoor air temperature of 26 ℃. Subjective evaluation was collected through a questionnaire. Blood oxygen saturation (SpO_2), skin temperature, and electrocardiograph (ECG) were measured. As expected, the overall thermal sensation, comfort, acceptability, preference, and subjective air freshness changed significantly before and after temperature step-changes. Perceived sweat and chest tightness were also affected by the temperature step-changes. Skin temperature, heart rate, time-domain, and nonlinear heart rate variability were affected significantly under temperature step-changes. We observed the overshoot phenomenon with thermal sensation and subjective air freshness under temperature down-step. Thermal sensation had a faster stabilization time than the measured physiological parameters (i.e., skin temperature, heart rate and heart rate variability) under temperature step-changes. The stabilization time before starting a thermal comfort experiment should be at least 30 minutes. Thermal sensation and skin temperature had an asymmetry effect on temperature step-changes.

Graphical abstract



Keywords: Thermal comfort; Temperature step-change; Physiological responses; Radiant cooling

1. Introduction

Radiant cooling systems have gained attention for their energy-saving potential [1-3]. In radiant cooling system, radiant heat transfer covers more than 50% of the heat exchange in the space [4]. Due to the large cooling panel area, radiant cooling systems can cool down the space with a lower temperature difference between the space and cooling source [5]. This may allow the usage of higher chilled water temperature and, therefore, may increase the chiller's efficiency. The high temperature of cooling source could make the radiant cooling system more efficient than all air central air conditioning system. Radiant systems usually create a more homogeneous environment than air systems and in a radiantly conditioned room mean radiant temperature (MRT) is closer to air temperature than in an all-air space [6]. Radiant cooling systems may also have the potentiality of equal or higher thermal comfort [7]. Compared to the all-air conditioning system, radiant cooling system has less air movement and smaller vertical temperature gradient [8]. Based on occupants' feedback, radiant cooling ceiling panel system created an environment with less draught than conventional systems [9]. Further, chamber experiments [10, 11] compared three all-air systems and three radiant scenarios. The results indicated that radiant cooling ceiling panel system reduced the cold discomfort in the lower part of the body. Subjects showed no preference for radiant cooling systems or all-air systems based on the subjective votes. A field study in 60 buildings (34 of which used all-air systems and 26 of which used radiant systems) involving almost 4000 participants found that radiant and all-air space have equal indoor environmental quality, including acoustic satisfaction, with a tendency towards improved temperature satisfaction in radiant buildings [12].

People usually experience transient thermal environments when entering or leaving a conditioned indoor environment. Many studies [13] have explored human comfort under the transient thermal environment with all-air conditioning systems. These studies observed the presence of the thermal sensation overshoot (aka, "overshoot phenomenon"). For example, after a step reduction in temperature, the thermal sensation decreases more than its value after steady state conditions are reached. The overshoot phenomenon is related to the skin temperature changes ("anticipatory effect") [14]. There is an asymmetry on the behavior depending on the direction of the step change (down-step vs up-step) [15]. The initial amplitude of thermal sensation change under temperature down-step was twice as the up-step one. This support the hypothesis that subjective sensitivity to temperature steps is correlated to the depth of thermoreceptors under the skin; cold thermoreceptors (0.15-0.17 mm) are closer to the skin than the warm thermoreceptors (0.3-0.6 mm) [16] and the fact that humans have more cold thermoreceptors than warm thermoreceptors. In an experiment, skin temperature and thermal sensation reached a steady state within about 20 min under temperature down-steps (34/ 37 °C – 31/ 28/ 22°C) [17]. The neutral temperature changed over time after the steps due to the thermal conditions before temperature changed [18]. In the hot humid area of China, overshoot occurred with thermal sensation in chamber experiments when the temperature steps were larger than 5℃ [19, 20].

Perspiration, eyestrain, dizziness, accelerated respiration and heart rate are self-reported symptoms that are affected by temperature step-changes [21]. In addition, several physiological parameters are affected by step-changes. For example, oral temperature, skin temperature, heart rate and heart rate variability and interleukin 6 (IL-6) [22-24]. Skin temperature and its change rate over time are used to predict dynamic thermal sensation during temperature step-changes [25-28]. Skin temperature, skin moisture [29] and heat loss [30, 31] are highly correlated to thermal sensation during temperature step-changes.

However, all studies mentioned above were performed in spaces conditioned by all-air systems. Given that MRT ≈ T_a in spaces conditioned by radiant system [6], we hypothesize to observe similar subjective and physiological responses than in all-air systems. To our knowledge, no study explored the thermal comfort in radiant environment under temperature step-changes and therefore we think it is important to experimentally verify it.

For the reasons explained above, we conducted human subject experiments to explore human thermal comfort and physiological responses in an environment conditioned with radiant ceiling panels under temperature up and down step-changes. We measured indoor physical and physiological variables, and we performed subjective psychological evaluations.

2. Methods

We conducted the experiment in two adjacent office rooms located in Hunan University, Changsha, China. Twenty healthy college students (9 male, 11 female) experienced transient conditions. The transient conditions consisted of three different temperature step-change intensities (i.e., C_{29}: 29-26-29 ℃; C_{33}: 33-26-33 ℃; C_{36}: 36-26-36 ℃). Participants experienced all experimental conditions balanced in Latin-square to exclude the potential learning effect. Each condition lasted two hours. The experiment used a single-blind design. We maintained the relative humidity at around 60% in all conditions. To simulate a standard indoor radiant cooling environment, we set the air temperature as 26 ℃; the surface temperature of the radiant ceiling panel was 20 ℃. For the simulated outdoor environment, we used 29, 33 and 36 ℃ to simulate slightly warm, warm, and hot outdoor environments, respectively. We collected subjective thermal perception and SBS symptoms through a paper questionnaire. We continuously measured indoor physical variables (i.e., air temperature, globe temperature, surface temperature, and relative humidity) by calibrated instruments, and monitored physiological responses (i.e., skin temperature, SpO_2, and ECG) by non-invasive instruments.

2.1 Human subjects

We required all recruited participants to not currently taking prescription medication, no history of cardiovascular disease, non-smokers and living in Changsha for more than one year. More than one year of living experience ensures their natural acclimatization to the local climate. We recorded their background information (i.e., age, height, weight). **Table S1** presents the descriptive statistic results of participants' anthropometric information. During the experiment duration, we forbade the alcohol intake, staying up and strenuous exercise with participants, but we did not verify compliance. All participants wore uniform clothing, including short pants and short-sleeve shirts. We determined the clothing insulation as 0.5 clo (ASHRAE 55) [32].

2.2 Experiment facilities

We conducted the experiment in two adjacent rooms (Room A: 4.3 m × 2.7 m × 3.0 m; Room B: 4.3 m × 2.0 m × 3.0 m) (**Figure 1**). The only external wall with windows was blocked with insulation cotton to exclude the effect of the outdoor environment. In the radiant cooling room, we used a wall-mounted air conditioner to dehumidify and cool the indoor air and portable air heater to reheat air. There was not an outdoor air ventilation system serving directly the rooms during experiment, air infiltrated from adjacent ventilated areas. We monitored the CO_2 but having a direct ventilation system would have been better. The radiant ceiling panel covered about 72% area of ceiling, which was hung 0.3 m lower than the ceiling. Total twelve water-cooled aluminum alloy panels formulated the radiant ceiling. Each panel (1200 × 600 × 20 mm) had 3.4 mm diameter of capillary tubes inside and was insulated with 20 mm rubber insulation layer. A outside cooling-water machine supplied and recirculated the cool water inside the capillary tubes. We can set the temperature of cool water supplied with the cooling-water machine between 10 and 24 °C. In this experiment, we controlled the supplied cool water temperature based on the designed surface temperature (20 ℃) of radiant ceiling panel. In outdoor environment, we used a wall-mounted air conditioner and portable air heater to maintain the indoor temperature and relative humidity.

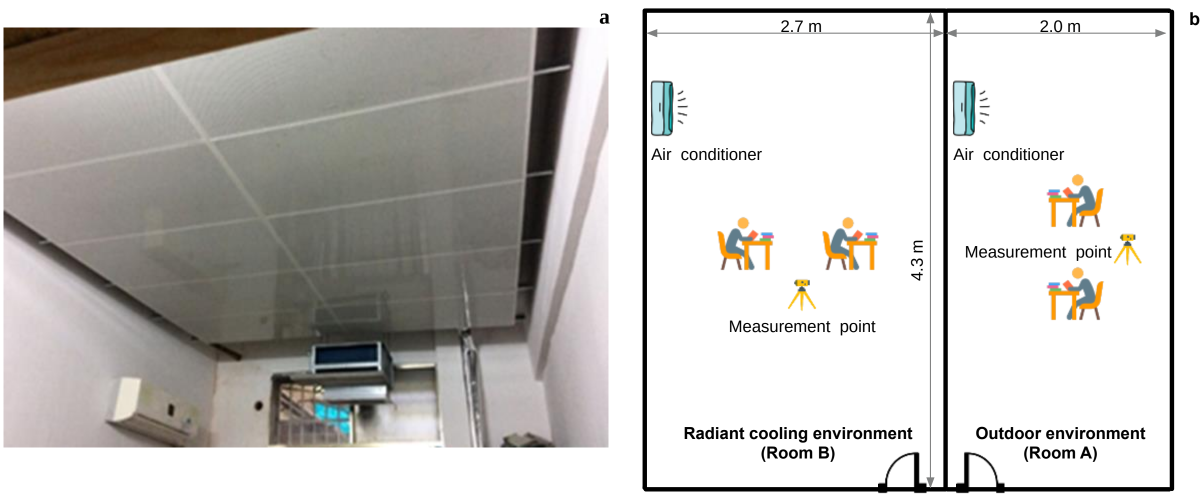


Figure 1 (a) layout of radiant cooling environment room and (b) experiment schematic diagram

2.3. Measurements

2.3.1. The environment measurements

The physical measurement consisted of radiant ceiling temperature, air temperature, globe temperature, and relative humidity. In the radiant cooling environment room, we monitored air velocity, air temperature, globe temperature, and relative humidity every 10 seconds with Thermal Index Instrument (HD 32.2; Delta Ohm, Italy). We placed three thermal index instruments near participants at three heights (e.g., 0.1, 0.6, and 1.1 m). There was problem with air velocity sensor at 0.6 height and therefore we only monitored the air velocity at 0.1m and 1.1 m. We measured the radiant ceiling panel temperature every 10 seconds with PT_{100} thermometer. A data logger stored PT_{100} thermometer data. In the outdoor environment room, Thermal Index Instrument monitored air temperature, globe temperature, and relative humidity every 10 seconds. We placed one Thermal index instrument at the height of 0.6 m near participants. **Table S2** presents the details of physical instruments. **Table S3** summarizes the test conditions. The temperature differences between the two rooms were 3 K in C_{29}, 6 K in C_{33}, and 10 K in C_{36}. We maintained the relative humidity in both rooms at about 60%. The mean air velocity in radiant environment room was lower than 0.05m/s. Air movement was not perceivable.

2.3.2. Physiological measurements

This study measured physiological responses including skin temperature, blood oxygen saturation (SpO_2), and electrocardiograph (ECG). **Table S4** lists the information of physiological instruments. We present the detailed description of physiological measurement as follows.

Skin temperature. In this study, we determined mean skin temperature with eight local skin sites (i.e., forehead, right upper arm, left forearm, left hand, left chest, right back, right thigh and left calf). **Figure S1** shows the exact locations of local skin sites. We attached the iButton sensors (DS1922L-F5#, Maxim Integrated, USA) to the skin surface with surgical tape, and sample rate was every 10s. According to ISO 9886 [33], we calculated mean skin temperature as the weighted average of eight local skin sites. We present the equation as follows,

$$T_{mst} = 0.07T_{forehead} + 0.175\ T_{chest} + 0.175\ T_{back} + 0.07\ T_{upperarm} + 0.07\ T_{lowerarm} + 0.05\ T_{hand} + 0.19\ T_{thigh} + 0.2\ T_{calf} \quad (1)$$

Where T_{skin} is the mean skin temperature.

Blood oxygen saturation (SpO_2). Blood oxygen saturation is an important indicator of the respiratory system reflecting oxygen concentration in blood. This study measured blood oxygen saturation every 1s by finger clip oximeter. We attached the oximeter to the left index fingertip.

Heart rate variability (HRV). Heart rate variability (HRV) is the time variation between two successive heartbeats. It is a non-invasive autonomic nervous system (ANS) activity marker. In this study, the portable ECG monitor (CCS-103, Careshine Electronic Technology, China) recorded the electrocardiogram (ECG) at a sampling rate of 500 Hz. We divided the original ECG data into 5-min-long ECG window segments to calculate the HRV indicators. The HRV usually consists of time-domain indices, frequency-domain indices and nonlinear indices. **Table 1** shows the description of the heart rate variability indices.

Table 1 Heart rate variability indicators

Heart rate variability	Definition
Time domain HRV indices	
Average RR	Average of RR intervals
RMSSD	Root Mean Square of the Successive Differences, RMSSD
SDRR	Standard Deviation of RR intervals
pNN_{50}	Percentage of RR pairs that differ by 50 milliseconds
Frequency domain HRV indices	
LF	Spectral power in low range frequencies (0.04-0.15Hz)
HF	Spectral power in high range frequencies (0.04-0.15Hz)
LF/HF	Ration between LF and HF power
Nonlinear HRV indices	
SD1	Short-term variability of the Poincare plot
SD2	Long-term variability of the Poincare plot

2.3.3. Subjective questionnaire

We used paper questionnaire to assess environmental conditions regarding subjective thermal perception, air freshness, and sick building syndromes symptoms. In the part of thermal perception, we explored overall thermal sensation based upon the ASHRAE 7-points scale (i.e., Hot (3), Warm (2), Slightly warm (1), Neutral (0), Slightly cool (-1), Cool (-2), Cold (-3)). Overall thermal preference was 7-point scale (i.e., Much warmer (3), Warmer (2), Slightly warmer (1), Neither warmer nor cooler (0), Slightly cooler (1), Cooler (2), Much cooler (3)). Overall thermal acceptability was 6-point scale (i.e., Clearly acceptable (2), Acceptable (1), Slightly acceptable (0.01), Slightly unacceptable (-0.01), Unacceptable (-1), Clearly unacceptable (-2)). Overall thermal comfort was 7-point scale (i.e., Very comfortable (3), Comfortable (2), Slightly comfortable (1), Neither comfortable nor uncomfortable (0), Slightly uncomfortable (-1), Uncomfortable (-2), Very uncomfortable (-3)). We also evaluated subjective air freshness and investigated several sick building syndromes symptoms (i.e., dry eyes, chest tightness, cough, dizziness, dry throat, rapid heart rate, stuffy nose, sweat) in terms of binary scale (Yes/No).

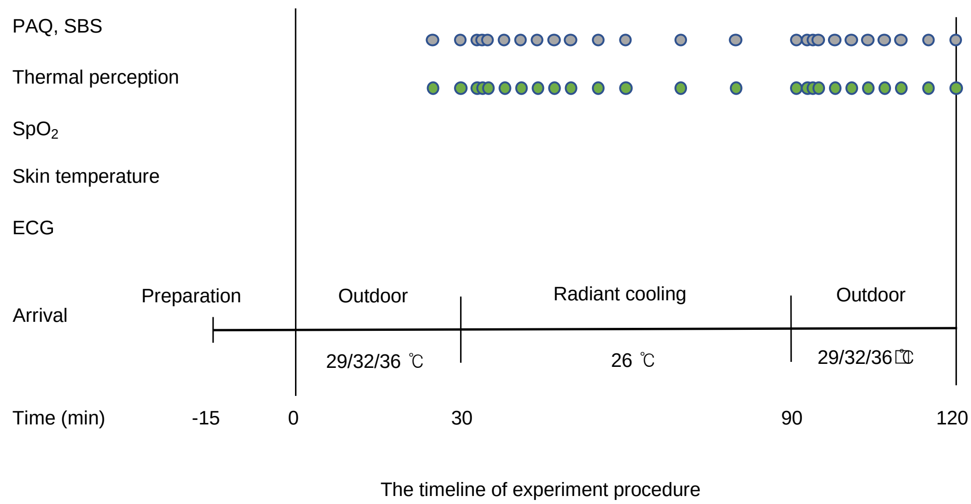


Figure 2 Experiment procedure. Each dot represent when the survey was done.

2.4 Experiment procedure

We conducted the experiments within four successive weeks. We assigned four experiment periods (i.e., 9:00-11:00, 13:00-15:00, 16:00-18:00, 19:00-21:00) every day with the same experimental condition. We randomly divided twenty participants into ten groups with two people. Each group accomplished all three conditions on three successive days during the same experiment period. **Figure 2** shows the experimental procedure. Each experiment condition lasted two hours. In the pre-stage, participants stayed in Room B (radiant cooling environment) spending 15 minutes attaching the physiological instruments (i.e., iButton, ECG monitor, and finger clip oximeter). Then participants entered Room A (outdoor environment) staying for 30 minutes. During this period, participants filled in the questionnaire. They evaluated air freshness, overall thermal perception, and sick building syndromes symptoms. Then participants entered Room B (radiant indoor environment), staying for 60 minutes. At the 90th minute, participants moved to Room A (outdoor environment) again and stayed 30 minutes.

2.5 Statistical analysis

We used SPSS software (IBM SPSS Statistics 22; IBM Corporation, Armonk, NY, USA) and R studio to perform the statistical analysis. The Shapiro-Wilk test determined the normality of data. We used the repeated-measures ANOVA or paired-sample t-test for distributed datasets, and the nonparametric test-Wilcoxon's test or Friedman test for abnormally distributed datasets. We conducted Generalized Estimating Equations and McNemar's Chi-squared Test for binary responses (SBS). We set the significance level to $p = 0.05$. We also used another statistic indicator, effect size (ES), in this study. The effect size [34] indicates whether the difference is of practical importance. For repeated measure ANOVA, we reported the ES values (η^2) of 0.01, 0.06 and 0.14 as small, moderate, and large effects, respectively. For means comparisons, the corresponding ES values (Cohens'd) are. 0.2, 0.5, and 0.8.

We determined the stabilization time with the ANOVA method. We performed ANOVA with the physiological and psychological responses from the initial time to the last time. If the statistical result was significant, we excluded the initial value until there was no significant effect with time ($P > 0.05$). Then the time was stabilization time.

3. Results

3.1. Subjective evaluation

3.1.1. Thermal comfort

Figure 3shows how the subjective thermal comfort varied over time for the three tested conditions. **Figure 3a** shows the overall thermal sensation (OTS). Overall thermal sensation decreased significantly when entering the radiant cooling environment ($P < 0.001$) in all conditions. The overshoot phenomenon existed at the initial stage and then OTS increased, reaching stable state within 4 min in C_{29}, 11 min in C_{33}, and 5 min in C_{36}. When re-entering the outdoor environment, OTS increased immediately and reached stability within 3 min in 29 ℃, 33 ℃, and 36 ℃. **Figure 3b** shows the overall thermal preference (OTP) tendency with time. When entering the radiant indoor environment, OTP increased significantly ($P < 0.001$). Then OTP reached stable state within 3 mins in C_{29}, C_{33} and C_{36}. When re-entering the outdoor environment, OTP decreased significantly ($P < 0.05$). Then OTP reached stable state within 3 mins. **Figure 3c** shows the tendency of overall thermal acceptability (OTA) with time. Upon entering the radiant indoor environment, OTA increased significantly ($P < 0.001$) and reached a stable state within 3 min in C_{29}, C_{33} and C_{36}. When re-entering the outdoor environment, OTA decreased significantly ($P < 0.05$) and became stable within 3 min. **Figure 3d** shows the variation of overall thermal comfort (OTC). OTC increased significantly ($P < 0.001$) upon entering the radiant indoor environment. Then OTC became stable within 20 mins in C29, 3 mins in C33, and 3 mins in C36. When re-entering the outdoor environment, OTC decreased significantly ($P < 0.05$). OTC reached stability within 3 min in 29 ℃, 33 ℃, and 36 ℃.

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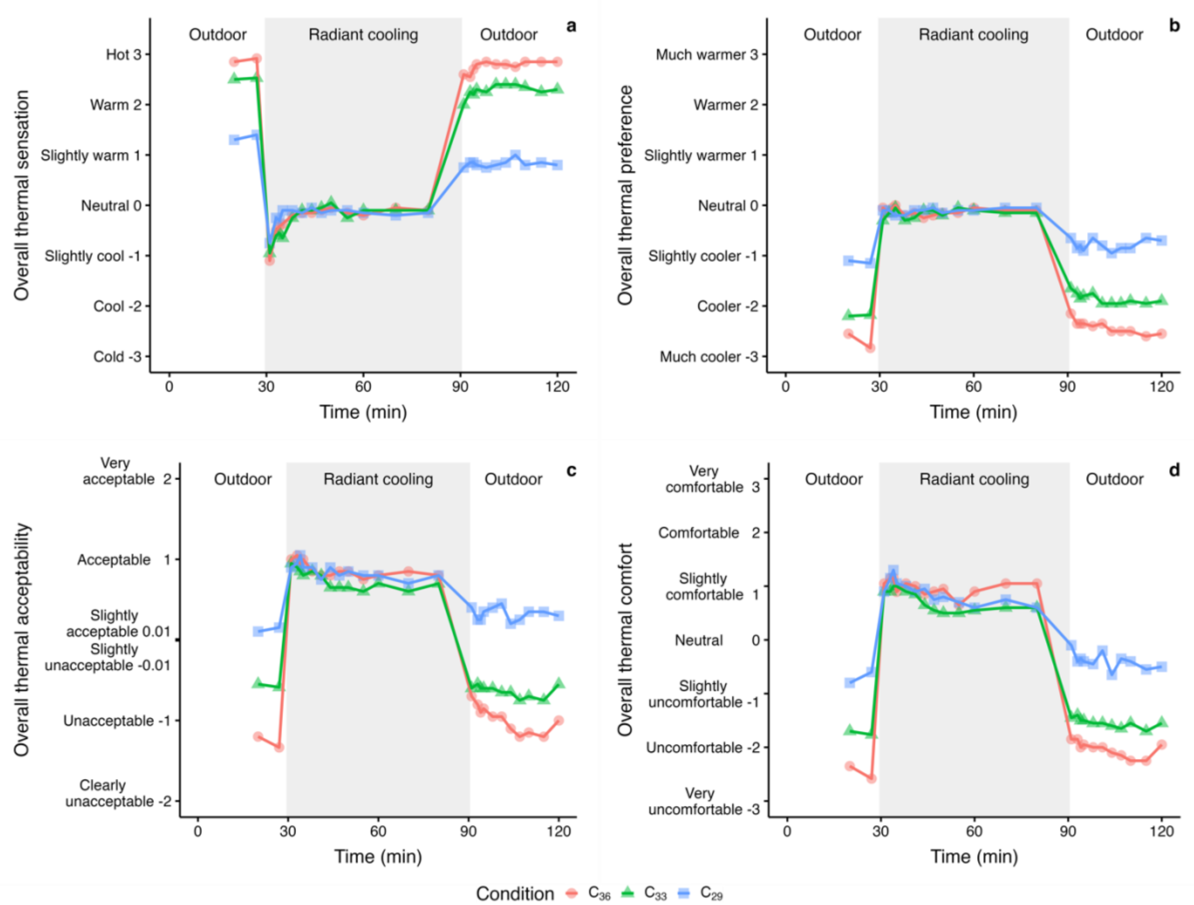

Figure 3 Time series of (a) thermal sensation, (b) thermal preference, (c) thermal acceptability, and (d) thermal comfort for the three tested conditions.

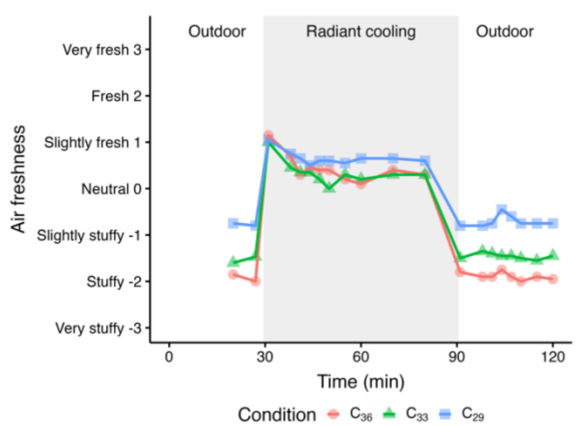

Figure 4 Time series of subjective air freshness for the three tested conditions.

3.1.2. Subjective air freshness

Figure 4 shows the change of subjective air freshness during exposure. Subjective air freshness was significantly higher at 29 ℃ than 33 ℃ and 36 ℃. Upon entering the radiant environment, subjective air freshness increased significantly ($P < 0.001$) reaching its maximum. Then subjective air freshness decreased and reached a stable state within 4 mins in C_{29}, 4 mins in C_{33}, and 11 mins in C_{36}. The overshoot phenomenon occurred with subjective air freshness in three conditions. When going back to the outdoor environment, subjective air freshness decreased immediately ($P < 0.001$). Subjective air freshness got stable within 3 mins in the three conditions.

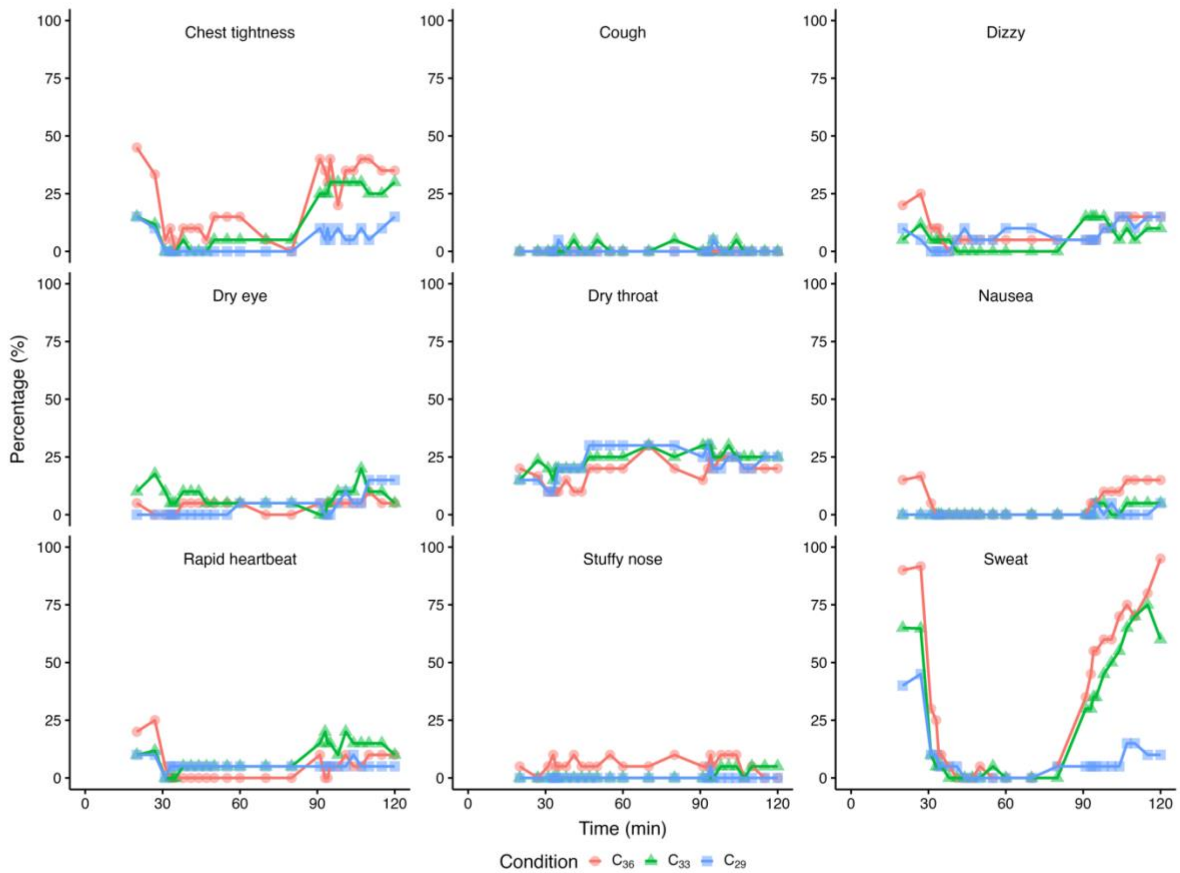

Figure 5 Time series of sick building syndrome for the three tested conditions.

3.1.3. Sick building syndrome symptoms

Figure 5 shows the prevalence of sick building syndrome (SBS) symptoms during the experiment. The percentage of most SBS symptoms, including dry eyes, cough, dizzy, dry throat, nausea, rapid heartbeat and stuffy nose was very low in both radiant cooling and outdoor environments. We found no significant change with these SBS symptoms under temperature down-step and up-step-changes. As shown in **Table 2**, the percentage of sweat was significantly lower in radiant cooling environment than that before temperature down step-changes in C_{29} and C_{33}. When experiencing temperature up-steps from the radiant cooling environment to warm outdoor environment, the percentage of chest tightness increased significantly in C_{36} and the percentage of sweat increased significantly in C_{33} and C_{36}.

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Table 2 The changes of SBS symptoms with regards to temperature step-changes

Symptoms	Temp. up-steps			Temp. down-steps		
	C_{29}	C_{33}	C_{36}	C_{29}	C_{33}	C_{36}
ΔChest tightness	10%	20%	40%*	10%	12%	33%
ΔSweat	0	30%*	30%*	35%*	55%**	62%**

* Δ, the percentage after step-changes minus the corresponding values before step-changes; *, P < 0.05; **, P < 0.01.

3.2. Physiological responses

3.2.1. Skin temperature

Figure 6a shows how the skin temperature changes during the experiment. Upon entering and leaving the radiant cooling environment, mean skin temperature decreased and increased quickly.

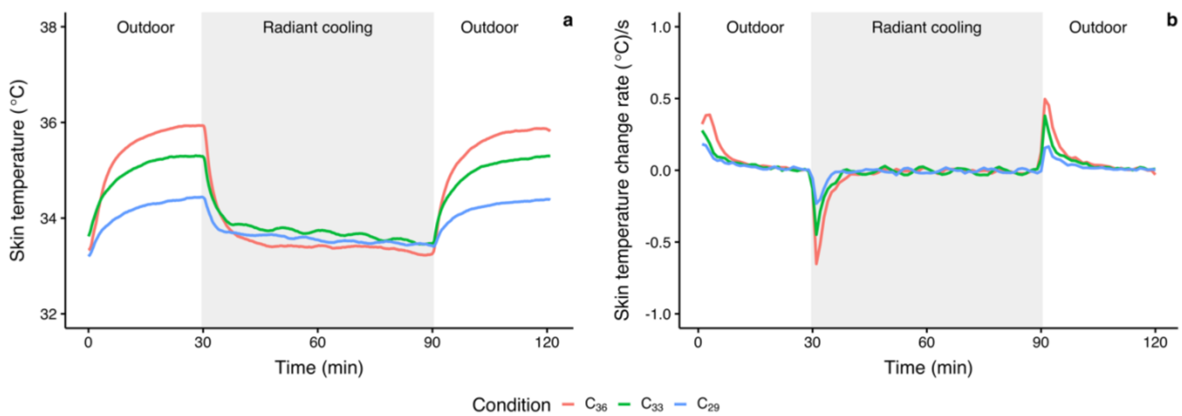

Figure 6 Time series of (a) skin temperature and (b) skin temperature change rate for the three tested conditions.

We performed a first-order difference analysis to model the skin temperature change. **Figure 6b** shows the change rate of mean skin temperature. The observed pattern indicates that the change rate of skin temperature follows the dynamic response of the first-order differential system. Therefore, under temperature step-changes, we can model the change of mean skin temperature as the step response of a first-order system. Based on control theory, we can model it as:

$$c(t) = A + (B - A)\left(1 - e^{-\frac{t}{\tau}}\right) \quad (2)$$

A is the stable mean skin temperature before the step-change, and B is the stable mean skin temperature after the step-change. τ is the time constant. When t is equal to an integer multiple of τ, namely t = τ, 2 τ, 3 τ, 4 τ, the response c(t) is 0.632, 0.865, 0.95, 0.982 times of the total change. τ reflects the inertia of the system. The smaller the τ, the lower inertia of the system. τ_{95} is the settling time. τ_{95} is the time required to reach 95% of its final value. It represents the dynamic response of the step-change.

This study divides the time into two periods for separately modeling skin temperature change. The first period includes the first outdoor and the radiant cooling phases; the second period includes the radiant cooling and the second outdoor phases.

When participants entered radiant cooling environment from outdoor environment, the mean skin temperature reached stable state within 12.6 mins in C_{36}, 18 mins in C_{33}, and 15.3 mins in C_{29} (**Table 3**). When returning to outdoor environment from radiant cooling environment, the mean skin temperature reached stable state within 16.5 mins in C_{36}, 21.9 mins in C_{33}, and 19.5 mins in C_{29}.

Table 3 The results of first-order dynamic response corresponding to skin temperature

Con	C_{36}: 36-26-36℃		C_{33}: 33-26-33℃		C_{29}: 29-26-29℃	
Parameters	36-26℃	26-36℃	33-26℃	26-33℃	29-26℃	26-29℃
B (℃)	33.32	35.83	33.60	35.28	33.45	34.31
A (℃)	36.09	33.05	35.25	33.39	34.39	33.30
τ (min)	4.2	5.5	6.0	7.3	5.1	6.5
τ_{95} (min)	12.6	16.5	18	21.9	15.3	19.5
R^2	0.981	0.994	0.949	0.997	0.918	0.991

3.2.2. Heart rate and blood oxygen saturation

Figure 7 shows the tendency of heart rate during experiment exposure. Heart rate increased significantly with temperature. Upon entering radiant cooling environment, heart rate decreased immediately in C_{36} ($P < 0.001$, $d = 2.29$), C_{33} ($P < 0.001$, $d = 1.19$), and C_{29} ($P < 0.001$, $d = 1.17$). Then heart rate continuously decreased and reached stable state within 30 mins in C_{29}, 30 mins in C_{33}, 40 mins in C_{36}. When re-entering outdoor environment, heart rate increased significantly in ($P < 0.05$, $d = 0.62$), C_{33} ($P < 0.001$, $d = 1.11$), C_{36} ($P < 0.001$, $d = 1.27$). Heart rate became stable immediately in C_{29} and C_{33}, within 10 mins in C_{36}. No significant difference was found on SpO_2 under step-changes.

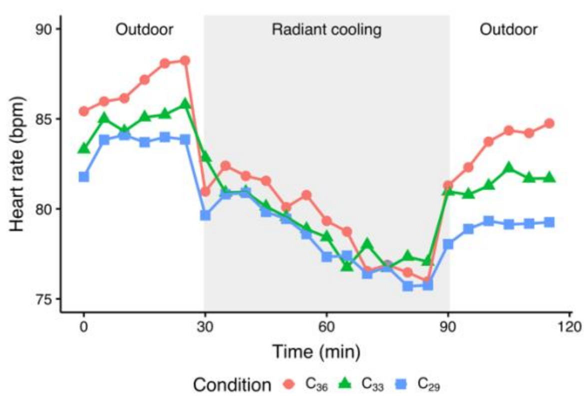

Figure 7 Time series of heart rate for the three tested conditions.

3.2.3. Heart rate variability

Figure 8 illustrates the variation of HRV indices with time. In outdoor phase, the Average RR, RMSSD, pRR50, HFm and SD1 was the lowest in C_{36}. Upon entering the radiant cooling environment, all time-domain HRV indices and nonlinear domain HRV indices increased significantly; HFm increased significantly in C_{36}; LFm and LF/HF decreased significantly in C_{36}. When leaving the radiant cooling environment, all time-domain HRV indices and nonlinear domain HRV indices decreased significantly; HFm decreased significantly in C_{36}; LFm increased significantly in C_{36}.

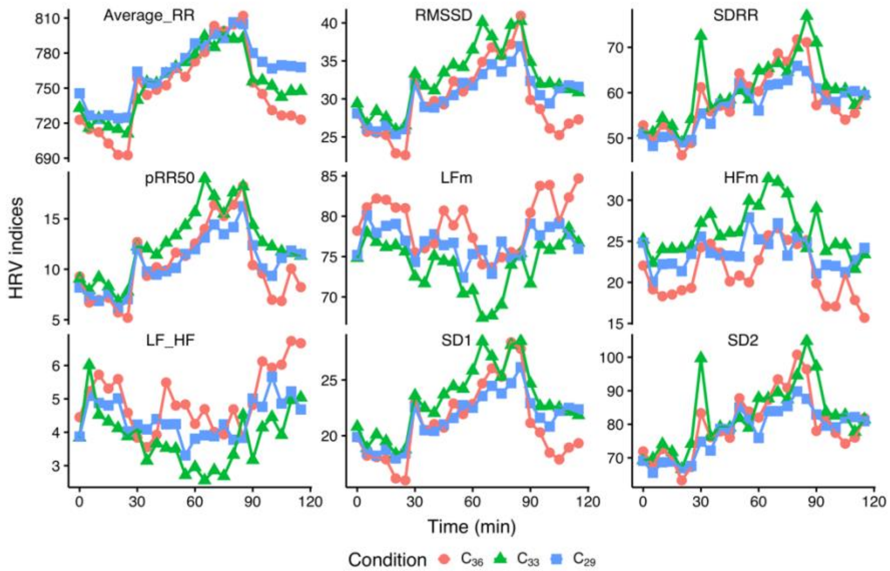

Figure 8 Time series of heart rate variability for the three tested conditions.

3.3. Asymmetry effects of temperature step-changes

To estimate the effect of temperature step-changes, we calculated the change magnitude (Δ), defined as the values after step-changes minus the corresponding values before step-changes. We determined the change magnitude of psychological responses as the first vote after step-changes minus the last vote before step-changes (i.e., ΔTS, ΔTP, ΔTA, and ΔTC). We calculated the change magnitude of physiological responses as the average value of the first 5 min after step-changes minus the average value of the last 5 min before step-changes.

3.3.1. Asymmetry effects on psychological responses

Figure S2 shows the asymmetry effects of temperature step-changes on thermal perception. The results indicated that the change magnitude of thermal sensation, preference, acceptability, and comfort was positively correlated to the change magnitude of temperature. For the direction of temperature steps, the change magnitude of thermal perception was larger in temperature down-step than in temperature up-step.

3.3.2. Asymmetry effects on physiological responses

Figure S3 shows the asymmetry effects of temperature step-changes on physiological responses. For temperature down-step, the temperature step intensity was positively correlated to ΔT_{mst}, ΔHR, and ΔRMSSD. Especially, ΔT_{mst} was significantly higher in C_{36} than in C_{33} and C_{29}; ΔAverage_RR was significantly higher in C_{36} than in C_{33}; ΔHR was significantly higher in C_{36} than in C_{29}. For temperature up-step, the temperature step intensity was positively correlated to ΔT_{mst}, ΔHR, ΔAverage_RR, ΔRMSSD, ΔpRR50, and ΔSDRR. ΔT_{mst} was significantly higher in C_{36} than C_{33} and C_{29}; ΔHR was significantly higher in C_{36} than C_{29}; ΔAverage_RR was significantly higher in C_{36} than those in C_{29}. As for the direction of temperature step-changes, no significant effect was found on the change magnitude of heart rate and all HRV indices. Under the same change magnitude of temperature step, the ΔT_{mst} was larger in temperature down-step than in temperature up-step. Especially, the ΔT_{mst} of C_{36} and C_{33} was significantly higher in temperature down-step than those in temperature up-step.

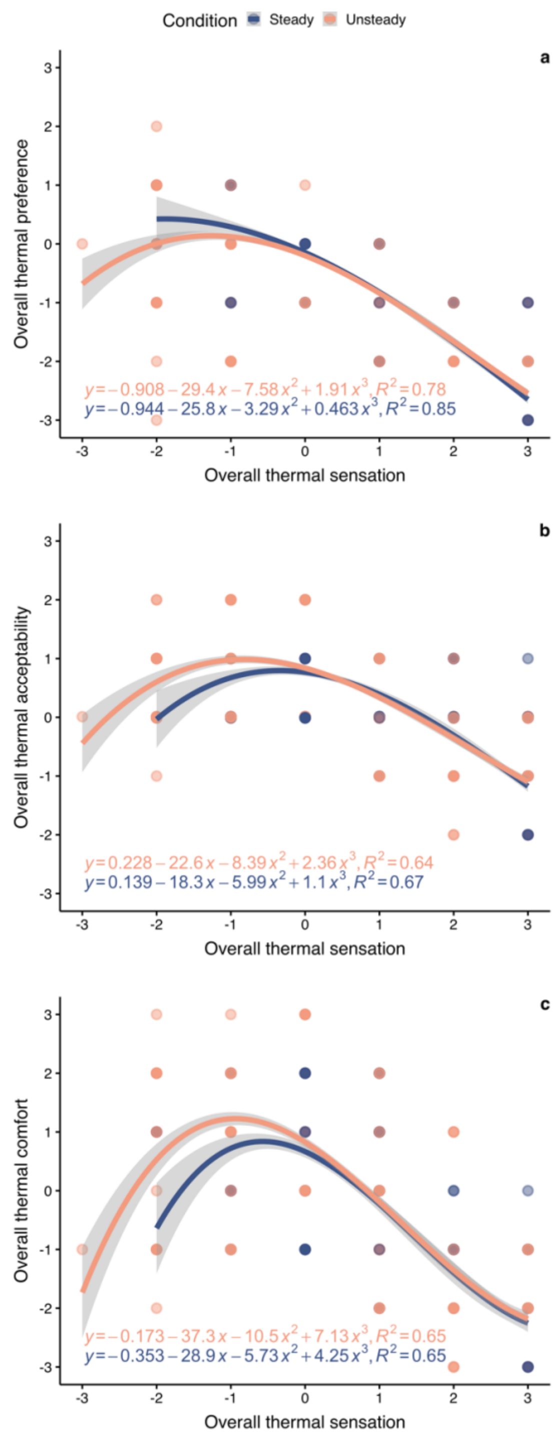

Figure 9 Relationship between (a) thermal sensation and thermal preference, (b) thermal sensation and thermal acceptability, and (c) thermal sensation and thermal comfort under unsteady and steady state

3.4. Relationship between physiological and psychological responses

3.4.1. Relationship among thermal perception

Based on the analysis of section 3.1, we defined the initial thermal responses within 20 minutes after temperature steps as the unsteady phase and those after 20 minutes as steady phase.

Figure 9 shows the comparisons between the unsteady and steady groups for overall thermal preference, acceptability and comfort with overall thermal sensation. The results indicated that the patterns were similar for the steady and unsteady responses. We established second-order polynomial functions to relate overall thermal preference, acceptability, comfort and overall thermal sensation. In both steady and unsteady phases, the most comfortable and acceptable sensation was close to 'Slightly cool'; the preferred sensation was on the cool side, close to 'Neutral'. The comfortable and acceptable sensation range was larger in unsteady phase than those in steady phase. Meanwhile, the most comfortable and acceptable sensation in unsteady phase was lower than those in steady phase.

3.4.2. Relationship between thermal sensation and physiological responses

Previous studies [16, 20, 26, 27] have revealed that thermal sensation in a dynamic environment consists of steady and dynamic components. We can express the dynamic thermal sensation as:

$$DTS = TS_{steady} + TS_{dynamic} \tag{3}$$

DTS is dynamic thermal sensation; TS_{steady} is the steady component correlated to the mean skin temperature; the dynamic item ($TS_{dynamic}$) is related to the change rate of mean skin temperature.

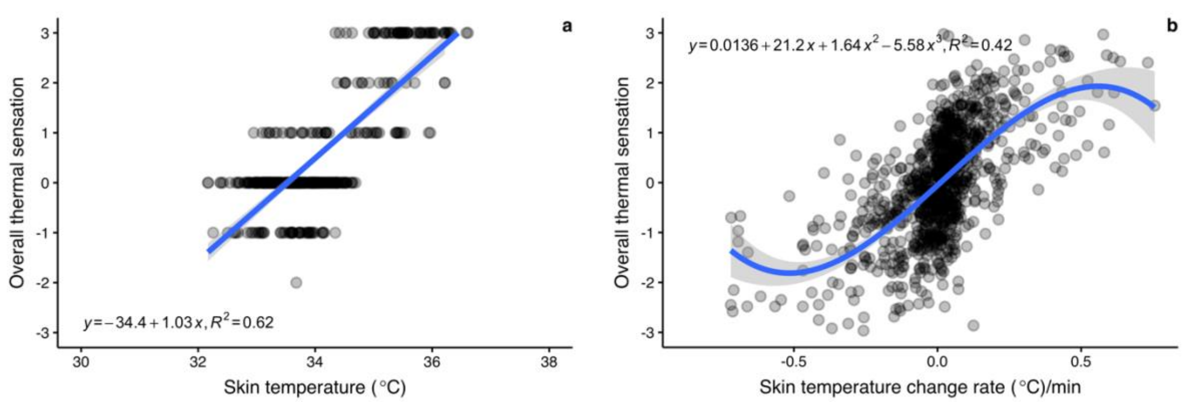

Figure 10 Relationship between (a)overall thermal sensation and skin temperature, and (b) overall thermal sensation and skin temperature change rate.

Based on the analysis of section 3.3, we regarded the initial skin temperature within 20 mins after temperature steps as the unsteady phase and those after 20 mins as steady phase. We established a linear relationship for the steady phase to link thermal sensation (TS) and skin temperature (T_{mst}). As shown in **Figure 10a**, the thermal sensation is highly correlated to skin temperature, and the skin temperature corresponding to neutral sensation was 34.4 ℃.

For the unsteady phase, we determined the TS_{steady} with the regression equation in steady phase. Based on equation (2), we calculated the $TS_{dynamic}$ by subtracting the DTS with TS_{steady}. **Figure 10b** shows that there is a cubic regression relationship with the calculated $TS_{dynamic}$ and change rate of skin temperature.

4. Discussion

The present study shows that human subjective perception and physiological responses changed significantly under temperature step-changes between an indoor environment conditioned by a radiant system and outdoor environments.

This study confirmed that radiant cooling systems create a homogeneous thermal environment. Given that the airspeed was low, the results indicated that $T_a \approx T_g \approx$ MRT (mean radiant temperature). This is similar to experiments [19-21, 23] of the all-air system under temperature step-changes because it is usually controlled to have $T_a = T_g =$ MRT. Therefore, the heat transfer in the indoor environment is similar between radiant cooling environment and all-air environment.

For SBS symptoms, chest tightness increased significantly in up-step of C_{36}. This demonstrated that increasing temperature induced the risks of asthmatic symptoms (chest tightness) [35, 36]. Subjective sweat symptoms decreased significantly in down-steps and increased significantly in up-steps except for C_{29}. This is consistent with the thermoregulation theory [37]. The thermoregulatory system will request heat dissipation through vasodilation and sweating when ambient temperature increases higher than the neutral setpoints. The same tendency of subjectively reported sweat also existed under temperature step-changes in all air system [21].

In line with previous studies [14, 17, 38], overshoot occurred with thermal sensation at the initial time after temperature down-step in the radiant cooling environment; we found no noticeable overshoot with thermal sensation after temperature up-step, which was consistent with the study by Liu et al. [30]. The results indicated that overshoot occurred for all the tested down-step changes, and the smallest temperature step was 3 ℃ (29 ℃– 26 ℃). However, Zhang et al. [19, 20] concluded that thermal sensation overshoot only when the temperature steps were larger than 5℃, which contradicts the findings in the present study. Zhang et al. [19, 20] concluded that overshoot was dependent on cooling intensity; they explained that the magnitude of the usual step-magnitude range of previous studies was 5-10 ℃ while the magnitude of the neutral-cool step-change in their study was within 3-6 ℃, which was not enough to induce overshoot. We are not sure why there is a discrepancy with overshoot between our study and Zhang et al. [19, 20]. One hypothesis is that the skin temperature decreased with time until the end of exposure when subjects experienced neutral-cool down-step-changes [19, 20]. The sum of the dynamic thermal sensation induced by change rate of skin temperature and the constant thermal sensation induced by skin temperature was almost the same with exposure time.

Subjective air freshness was fresher as temperature decreased [39-41]. Overshoot occurred with subjective air freshness after down-step in this study. The underlying mechanism is similar to the overshoot of thermal sensation. Subjective air freshness was linearly correlated with ambient air enthalpy and was related to the evaporative and convective cooling of the mucous membranes in the upper respiratory tract. Under down-step, the temperature of the mucous membrane may decrease, and the change rate of mucous membranes temperature induces an additional effect on subjective air freshness.

This study found that the stabilization time (defined in section 2.4) of thermal sensation in radiant cooling environment after temperature down-step was positively correlated to the magnitude of down-step-change except for the condition of C_{36}. The reason was that subjects perspired profusely; a large amount of moisture is accumulated in clothing when the outside temperature was 36 ℃ and then it evaporated and cooled the skin immediately entering radiant cooling environment, which makes the subjects reach stability very fast. Many studies have also mentioned the stability time of thermal sensation (Table 3). The stability time of thermal sensation under down-step-changes was consistent with previous studies, which was positively correlated to the magnitude of down-step change. In this study, the change magnitude of skin temperature was positively correlated to the change magnitude of down-step. Existing studies mainly determined the stability time of skin temperature using within-subject ANOVA and nonlinear fitting regression. It's reasonable to compare this study and other studies using the nonlinear fitting method. The stability time of down-step in 36 ℃ - 26 ℃ was 13 min in this study, similar to the same sceneries in Refs. [21, 23] under 37℃ - 26 ℃ (16 min) and Refs. [17] under 37℃ - 26 ℃ (18 min). This study suggests that the acclimatization time should be at least 30 min for subjects to reach steady state. This is consistent with most experiments conducted in steady state, which use 30 min as acclimatization time.

This study also confirms that changes in the collected psychological responses (thermal perception) are always ahead of the measured physiological responses (i.e., skin temperature, heart rate and heart rate variability) under step-changes. Namely thermal sensation, thermal acceptability, thermal preference, and thermal comfort reached stability within a shorter time than skin temperature under step-changes. These findings are consistent with the studies listed in **Table 4**. We can ascribe this phenomenon to the change rate of skin temperature inducing additional thermal sensation under unsteady state. In this study, we obtained a highly correlated linear relationship between dynamic thermal sensation and the change rate of skin temperature under the unsteady state [19]. Under the down-step, skin temperature changed greatly during the unsteady period, and the change rate of skin temperature produced a dynamic term of thermal sensation; the dynamic term pushed forward the change of thermal sensation greatly, resulting in a short stability time.

Table 4 Stability time for thermal sensation and skin temperature in different studies

Refs.	Conditions/ ℃	Stability time for thermal sensation/ min (analysis method)	Stability time for skin temperature/ min (analysis method)
[30]	32-25-32 30-25-30 28-25-28	10 min for down-step and 20 min for up-step 8 min for down-step and 20 min for up-step 6 min for down-step and 20 min for up-step (Within-subject ANOVA)	10-15 min for up-step 20 min for down-step (Within-subject ANOVA)
[20]	26-20-26 26-23-26 26-29-26 26-32-26	1 min for down-step and 5 min for up-step 1 min for down-step and 1 min for up-step 11 min for down-step and 1 min for up-step 14 min for down-step and 20 min for up-step (Within-subject ANOVA)	> 60 min for down-step and > 30 min for up-step > 60 min for down-step and > 30 min for up-step > 30 min for down-step and 50 min for up-step > 30 min for down-step and 50 min for up-step (Within-subject ANOVA)
[19]	26-20/23/32/29	1 min, 1 min, 1 min and 1 min, respectively (Within-subject ANOVA)	> 60 min, > 60 min, 30-40 min and 3 min respectively (Within-subject ANOVA)
[17]	34-28/25/22 37-31/28/25	About 20 min	5 min, 7 min and 31 min, respectively 17 min, 15 min and 18 min, respectively (Nonlinear fitting)
[21, 23]	22-37-22 26-37-26 32-37-32	1 min for down-step and 33 min for up-step 1 min for down-step and 1 min for up-step 1 min for down-step and 1 min for up-step	34 min for down step and 27 min for up-step 16 min for down step and 17 min for up-step

		(Within-subject ANOVA)	13 min for down step and 17 min for up-step (Nonlinear fitting)
[29]	32/28/20-24	Approximately 20 min (Not mentioned)	Approximately 10 min (Not mentioned)
[42]	20/23/29/32-26		15 min, 15 min, 20 min and > 20 min, respectively (t-test)
This study	29-26-29 33-26-33 36-26-36	4 min for down-step and < 3 min for up-step 11 min for down-step and < 3 min for up-step 5 min for down-step and < 3 min for up-step (Within-subject ANOVA))	15 min for down-step and 20 min for up-step 18 min for down-step and 22 min for up-step 13 min for down-step and 17 min for up-step (Nonlinear fitting)

Conforming to previous studies [21, 29], the magnitude of temperature step-change is positively correlated to the change magnitude of subjective perception and physiological responses. The larger step magnitude caused larger change magnitude of thermal perception, subjective air freshness, skin temperature, heart rate and Average_RR.

This study also confirmed that an asymmetry [21] exists in psychological and physiological responses. Under the same magnitude of temperature step-change, the change magnitude of thermal sensation and skin temperature was larger in the down-step than the corresponding values in the up-step. The results revealed that human was more sensitive to cooling with stronger physiological and psychological reaction intensity. This is because humans have ten times [43] more cold thermoreceptors than warm thermoreceptors [44], and the location of the cold thermoreceptors (0.15-0.17 mm) is more superficial than that of the warm thermoreceptors (0.3-0.6 mm) in the intracutaneous region [43].

Zhang et al. [45] have pointed out that the relationship between thermal sensation and comfort under steady state does not apply to dynamic conditions. The present study confirms it. Thermal acceptability and comfort were higher, and preference was lower under unsteady state than those in steady state when thermal sensation was lower than “Neutral”. The thermal alliesthesia concept [46, 47] states that a peripheral thermal stimulus that offsets or counters a thermoregulatory load-error will be pleasantly perceived and vice versa, a stimulus that exacerbates thermoregulatory load-error will feel unpleasant. Under down-step, subjects experienced overshoot with thermal sensation and large change rate of thermal sensation. The potential explanation is that thermal sensation change over time may have an additional impact on comfort and acceptability under an unsteady state. The change making sensation back to neutral produces more comfort.

In this study, skin temperature changed significantly due to vasodilation and vasoconstriction under step-changes [20, 22, 30]. The underlying physiological mechanism is that the thermoregulatory center requests heat dissipation through vasodilation and sweating when ambient temperature increases higher than the internal setpoint under up-step. Meanwhile, vasoconstriction happens when the ambient temperature increases higher than the internal setpoints under the down-step. As a marker of autonomic nervous system (ANS) activity, heart rate variability (HRV) is also highly correlated to human homeostasis [48]. The hypothalamus controls various mechanisms to maintain the core temperature. Homeostasis is the interaction actions of the parasympathetic nervous system (PNS) and the sympathetic nervous system (SNS). The SNS increases the heart rate (HR) while the PNS has an adverse effect. LF_m is related to SNS [49] while pRR50, RMSSD, Average_RR, and HF_m are markers of PNS [50]. LF/HF is acknowledged as an indicator of the interaction between LF and HF. Consistent with previous studies, HR was positively correlated to temperature [51, 52] and changed significantly under temperature step-changes [19, 24]. HRV was greatly affected by ambient temperature. All time-domain HRV indices, nonlinear domain HRV indices, and HF_m increased under temperature up-step and decreased under down-step. LF_m and LF/HF_m decreased under temperature up-step and increased under down-step. In Refs. [24], the Average_RR, SDRR, RMSSD and HF_m also decreased under temperature up-step and increased under temperature down-step; LF_m and LF/HF_m increased under temperature down-step and decreased under temperature down-step. Consistent with previous studies [24], time-domain HRV indices, nonlinear domain HRV indices, and HF_m can indicate the PNS activity while LF_m reflects the SNS activity; LF/HF indicates the interaction of ANS.

This study confirmed that ECG and skin temperature [53-55] can be valid physiological indicators supporting subjectively evaluated thermal comfort. The finding of dynamic change of thermal pleasure can provide fundamental knowledge for architects to design buildings or spaces eliciting thermal pleasure in a dynamic environment. Meanwhile, based on the solid relationship between physiological responses and thermal comfort, engineers can have a deeper understanding of the human building interaction. This study reveals that engineers could use bio-signals to implement automatic building management systems [56]. ECG and skin temperatures can be applied for monitoring occupants' instant satisfaction to improve building management system operation based on their preference. However, this study was conducted with only young and healthy college students. Usually, people walk in outdoor environment and they will experience activity step-change. We did not consider the step change of activity level, which should be further explored. Generally, a radiant cooling system includes both radiant cooling panel (handling with indoor internal sensible cooling load) and a ventilation system (remove indoor latent cooling load and providing fresh air). In this study, we firstly dehumidified the indoor air with the AC unit and then heated it with the portable heater. This is also a limitation of this work.

5. Conclusions

This study explored human thermal comfort, SBS symptoms and physiological responses to temperature step-changes in a space cooled by a radiant ceiling system. We observed that the cool thermal sensation and subjective air freshness overshot in the radiant cooling environment under temperature down-steps. We also found an asymmetry effect on thermal sensation and skin temperature regarding the direction of temperature step-changes. Thermal perception reached steady state faster than the skin temperature. Subjective air freshness, self-reported sweat and chest tightness changed significantly before and after temperature step-changes. Skin temperature, heart rate, time-domain and nonlinear HRV indices also changed significantly. The stabilization time of thermal sensation and skin temperature in the radiant cooling environment after temperature down-step was positively correlated to the magnitude of down-step change except for C_{36}. We showed that thermal sensation was highly correlated to skin temperature and its change rate in dynamic scenarios.

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.

Acknowledgements

This work presented in this paper was financially supported by the National Natural Science Foundation of China (Project No. 51878255). Z. Wu would like to thanks the Alexander von Humboldt Foundation of Germany for his postdoctoral fellowship at the Karlsruhe Institute of Technology. Z. Wu would also like to express his gratitude to Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) for the support at the Republic of Singapore's National Research Foundation. BEARS has been established by the University of California, Berkeley as a centre for intellectual excellence in research and education in Singapore.

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Supplementary Information

Tables

Table S1 The information of respondents

Gender	N	Age	Height (cm)	Weight (kg)	BMI (kg/m^2)	Dubios (m^2)
Male	11	23.9±1.2	174.5±3.6	65.0±6.7	21.3±1.9	1.87±0.09[a]
Female	9	22.2±1.9	158.4±4.2	49.4±10.4	19.7±4.2	1.57±0.14
Total	20	23.1±1.8	166.9±9.1	57.6±11.6	20.6±3.2	1.73±0.19

[a] Standard deviation

Table S2 The information of physical instruments

Parameters	Instrument	Range	Accuracy
Air temperature		-40-100℃	±0.1℃
Relative humidity	HD 32.3	5-98%RH	±2%RH
Globe temperature		0-50℃	±0.6℃
Ceiling temperature	PT_{100} thermometer	0-100℃	±0.15℃

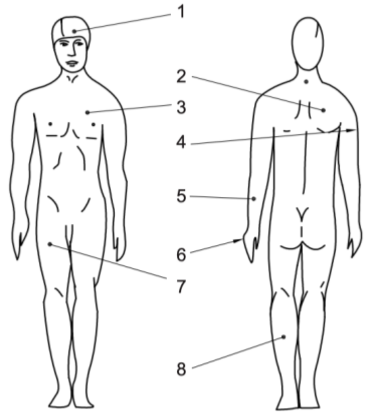
Table S3 The results of experiment condition

Con	C_{29}			C_{33}			C_{36}		
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
T_a (℃)	29.1±0.5	26.0±0.4	29.1±0.5	32.6±0.4	26.0±0.3	32.7±0.5	36.0±0.9	26.1±0.5	35.8±0.9
RH (%)	65±5	58±3	66±5	61±4	59±3	61±4	56±6	60±4	56±6
T_g(℃)	29.0±0.6	25.6±0.3	29.1±0.6	32.5±0.5	25.6±0.3	32.6±0.6	36.0±0.8	25.6±0.5	35.9±0.6
T_r(℃)	29.1±0.5	25.6±0.3	29.0±0.7	32.6±0.5	25.5±0.3	32.7±0.8	36.0±0.6	25.6±0.5	35.8±0.7
T_{ceil}(℃)		21.2±0.6			21.0±0.5			20.9±0.4	
V (m/s)	0.03±0	0.02±0	0.02±0	0.03±0	0.02±0	0.02±0	0.01±0	0.04±0	0.02±0
Co2 (ppm)	933±221	1090±225	1102±220	1095±225	1054±218	1159±179	1855±1121	1206±234	1948±1121

Table S4 Detail information of physiological instrument

Parameters	Instrument	Range	Accuracy
ECG	CCS-103	-	-
SpO2	Prince-100H	35-100%	±2
Skin temperature	DS1922L-F5#	20-75℃	±0.5℃

Figures



1: Forehead 2: Back 3: Chest 4: Upper arm 5: Lower arm 6: Hand 7: Thigh 8: Calf

Figure S1 Location of skin temperature measurement

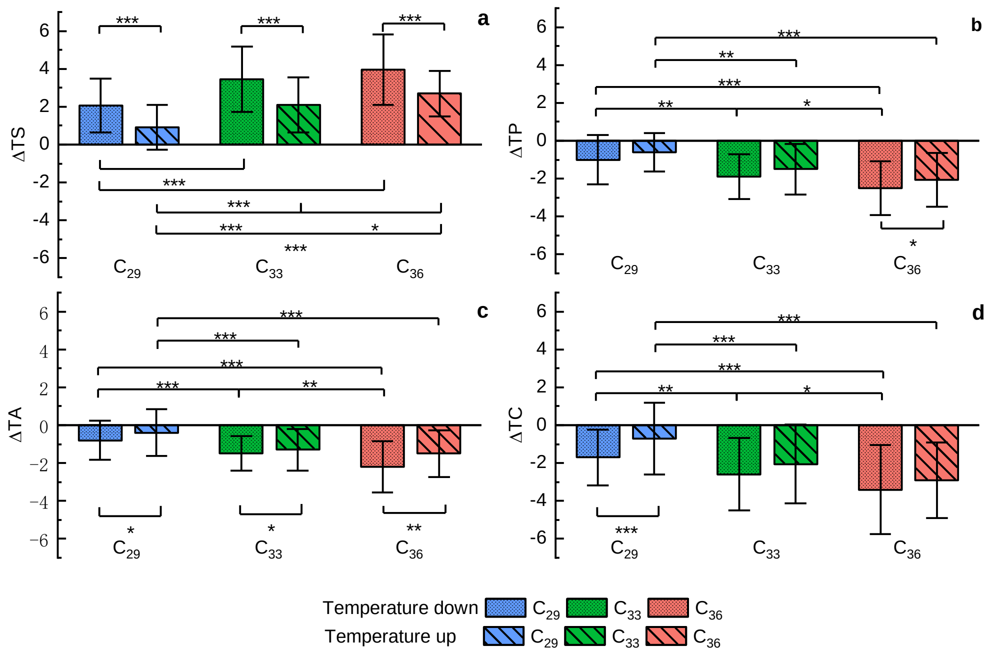


Figure S2 The asymmetric effect of temperature step-change on (a) overall thermal sensation, (b) overall thermal preference, (c) overall thermal acceptability, and (d) overall thermal comfort.

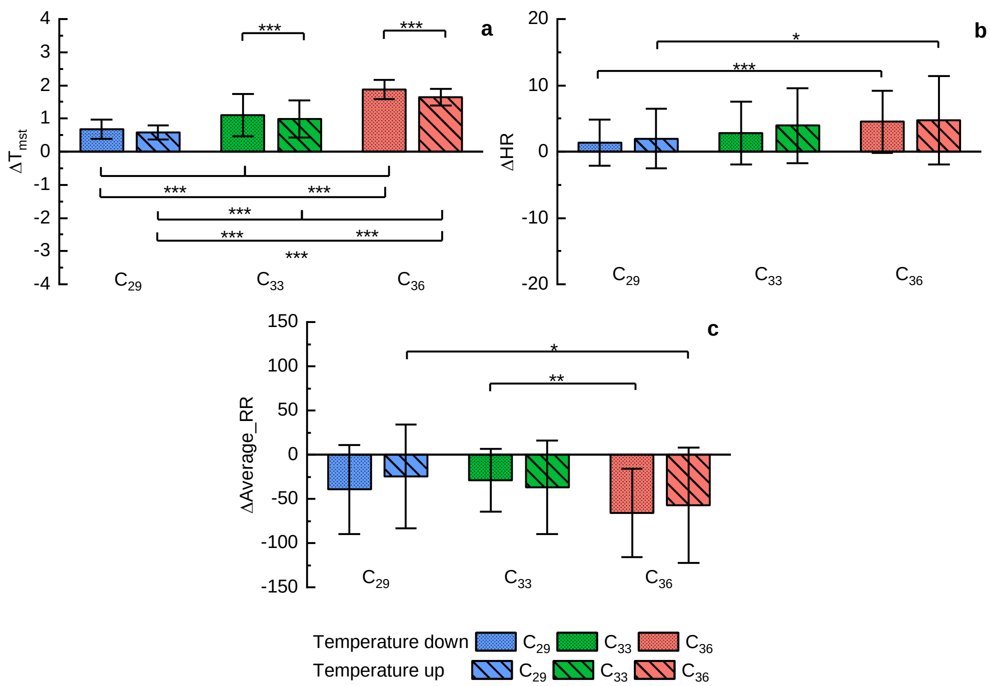


Figure S3 The asymmetric effect of temperature step-change on (a) mean skin temperature, (b) heart rate, and (c) Average RR.

 https://doi.org/10.1016/j.buildenv.2022.109512,