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Effects of intermittent cooling on human thermophysiological and perceptual responses in a non-steady-state thermal environment

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Abstract

Intermittent cooling, characterized by the on-off cycling of air-conditioning systems, generates a non-steady-state indoor thermal environment. While widely adopted for energy conservation, its impact on human thermophysiological and perceptual dynamics remains insufficiently understood. To investigate this, we conducted chamber experiments in a simulated residential/office space using three cooling set-points (thermostat target temperature: 28 °C, 26 °C, and 20 °C). Each trial involved 70 minutes of active cooling followed by 50 minutes of shutdown. We continuously monitored indoor air temperature, skin temperature, blood pressure, heart rate, and subjective thermal responses from 12 participants throughout each cycle. Results show that cold exposure intensity significantly shaped the temporal dynamics of human thermal response. Under strong cooling (20 °C), skin temperature declined continuously without stabilization over 70 minutes, thermal sensation and acceptability remained unstable until 35 - 40 minutes, and cardiovascular responses (e.g., DBP, HR) were only activated after prolonged exposure, stabilizing after > 50 minutes. In contrast, moderate and weak cooling (26 - 28 °C) enabled most physiological and perceptual responses to stabilize within 15 - 25 minutes. Asynchronous was observed among systems: skin temperature stabilized earliest, followed by perceptual responses, while cardiovascular regulation remained notably delayed under stronger cooling. After AC shutdown, overall recovery occurred within

35 minutes transitional timeframe, during which the effects of residual cold exposure continued to influence thermal perception and physiology. Based on these findings, we propose a theoretical framework for a “Cumulative Thermal Stimulus (CTSI)” index that integrates thermal deviation and exposure duration, offering a quantitative tool for adaptive cooling strategies that optimize comfort, health, and energy efficiency.

Keywords: Intermittent cooling; Thermal adaptation; Cold load intensity; Energy efficient HVAC controls

1 Introduction

In the context of global climate change, the frequent occurrence of extreme hot weather is driving rapid growth in building cooling energy consumption^[1,2]. Air conditioning, as the main means of cooling^[3], has become a significant source of carbon emissions while safeguarding the indoor thermal environment^[4,5]. Global air conditioning usage will continue to climb in the coming decades^[6], and the increasing energy demand for air conditioners will place higher demands on the electrical grid^[7]. Intermittent cooling refers to a non-continuous operation mode of air-conditioning systems, in which indoor temperature fluctuates over time due to user-controlled on-off behaviors, resulting in temporally and spatially non-uniform thermal environments. Intermittent cooling — a non-continuous air-conditioning operation mode — is widely adopted in residential and small office buildings, especially in regions characterized by the widespread use of split-type or window AC unit. Field studies suggest that over 70.0 % of residential users in hot climates (e.g., China, Southeast Asia) employ intermittent strategies, often driven by cost concerns, intermittent occupancy, or personal comfort preferences^[8,9].

Recent studies on dynamic thermal environments have extensively examined human responses to step changes, gradual drifts, and cyclic variations in air temperature. These experimental models have revealed valuable insights into environmental, physiological, and perceptual dynamics under non-steady-state conditions. For instance, step-change scenarios (Fig. 1a) highlight phenomena where thermal sensation changes more rapidly than the body’s physiological recovery rate, briefly crossing the neutral state, while physiological responses develop more slowly than the corresponding sensory changes; gradual temperature transitions (Fig. 1b) help delineate delayed regulatory responses; while cyclic environments (Fig. 1c) simulate real world oscillations and uncover rhythm-based adaptation patterns.

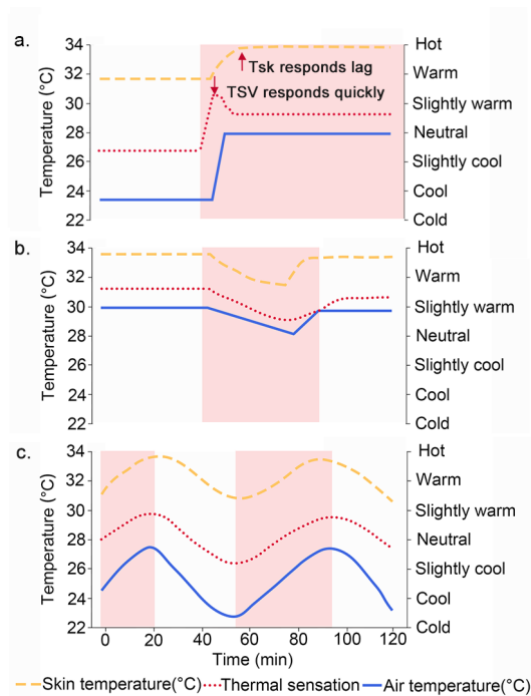


Fig. 1 Representative patterns of dynamic thermal environments and associated human responses.
a. Step-change environment^{[13][14][18]}

Simulating air-conditioner shutdown or set-point adjustment, an abrupt temperature rise from 23 °C to 28 °C caused thermal sensation to respond rapidly—while skin temperature lagged due to thermal inertia and delayed thermoregulation. This asynchrony highlights the divergence between perceptual and physiological responses in dynamic thermal environments.

b. Gradual-change environment^{[10][11]}

A slowly decreasing air temperature profile leads to corresponding skin temperature and thermal sensation shifts. This condition reflects a non-abrupt thermal drift and demonstrates the slower adaptation of both physiological and perceptual responses over time.

c. Cyclic thermal environment^[12]

Alternating warm and cool phases simulate cyclical thermal exposures, resembling periodic HVAC cycling. The figure shows rhythmic fluctuations in air and skin temperatures, with thermal sensation voting tracking a lagged but synchronized adaptation pattern.

However, air-conditioning systems, particularly under intermittent usage, often introduce dynamic thermal fluctuations into indoor environments. Unlike steady-state thermal conditions, these fluctuations lead to multi-phase, uneven cold exposure, presenting new challenges to the human thermoregulatory system and comfort perception. Specifically, such environments involve two interacting variables — temperature difference (ΔT) and exposure duration (t) — that jointly generate complex physiological and psychological responses.

Among environmental factors, air temperature changes have been shown to exert pronounced effects on thermal sensation and physiological regulation. Due to the human body's high sensitivity to temperature variation, numerous studies have focused on the impact of temperature difference (ΔT) on thermal sensation and physiological responses. Gagge et al.^[13] first reported that sudden ambient temperature changes induce perceptual overshoot and lag effects. Later studies confirmed that large temperature shifts trigger rapid fluctuations in skin

temperature, reduced thermal comfort, and elevated heart rate variability. For instance, Chen et al.^[14] observed thermal overshoot under an 8 °C temperature drop, while Xiong et al.^[15] found that larger temperature steps disrupted the correlation between thermal sensation and skin temperature. Similarly, Liu et al.^[16] reported intense physiological oscillations under an 11 °C shift, and Zhou et al.^[17] noted acute increases in heart rate and HRV under cold stimuli in severe climates, indicating that cold exposure may elevate physiological load. Moreover, the direction of temperature change is very important. Existing research has found that in a short-term temperature step environment, thermal sensation and skin temperature reach stability more quickly during the temperature drop phase than during the temperature rise phase.^{[15][16]}

In addition to temperature differences, the duration of exposure also significantly affects the human body's thermal response. Some studies suggest that prolonged exposure may impose cumulative stress on the circulatory and metabolic systems. For example, in cold environments, heat exchange between the skin and air may take up to three hours to reach equilibrium^[20]. Zhang et al.^[21] found that after exposure exceeds one-hour, subjective thermal sensation and comfort gradually deviate from neutral levels. Song et al.^[22] emphasized the temporal mismatch between physiological adaptation and perceptual adaptation during thermal exposure. Additionally, prolonged exposure to a constant thermal environment may impair thermal adaptation capacity, thereby altering comfort thresholds^[20,21].

Despite extensive studies examining either temperature difference or exposure time in isolation, existing studies on temperature differences and exposure duration have mostly focused on extreme temperature environments^[22-24] and long-term indoor and outdoor studies^[25-27], with few studies conducted in intermittent cooling environments. Most existing work focuses on single indicators such as thermal sensation or mean skin temperature^[31], with limited attention to the asynchronous, multi-phase nature of physiological and perceptual regulation. While both large ΔT and long exposure durations have been shown to increase thermal discomfort and physiological load, their combined effects remain poorly understood. Moreover, there is a lack of quantitative indices to characterize the compound “time \times intensity” effects of cold exposure.

In terms of research scenarios, the closest thing to the “intermittent cooling” usage characteristics is the study of mixed-mode buildings^[32]. However, such studies tend to focus on field surveys of air conditioning usage behavior^[30,31], thermal comfort^[32,33], or energy saving potential^[34,35], lacking a temporal empirical analysis of the entire physiological-psychological response process under controlled conditions. In particular, the regulatory characteristics during the accumulation of cooling loads and the critical recovery period remain

poorly understood.

Therefore, the aim of this study was to investigate the human thermal response under intermittent cooling conditions by controlling the temperature change and exposure duration. We propose a theoretical index “Cumulative Thermal Stimulus Index (CTSI)” to reflect the compound effect of intensity and duration, thereby shifting the research paradigm from static load evaluation to dynamic regulation analysis. This work provides a foundation for developing intelligent cooling strategies that integrate environmental, physiological, and perceptual dimensions. Specifically, the objectives of this study are to:

(1) Describe the temporal evolution of physiological and psychological responses under different cold exposure intensities, and identify key stabilization periods during cooling and recovery.

(2) Compare regulation patterns of human thermal responses during air-conditioning start-up and shutdown phases, and analyze how these patterns vary with exposure intensity and duration.

(3) Introduce the CTSI framework to quantify cumulative thermal load effects and support adaptive control strategies for air-conditioning systems in real-world buildings.

2 Methodology

2.2 Experimental site

The experiments were conducted in a room located at a university in Jiaozuo City, China, equipped with a floor-standing split-type air-conditioning unit. The room measured 5.8 m × 4.9 m × 3.8 m (L × W × H) and featured a typical brick concrete structure. To avoid the impact of precipitation or cloud cover, all experiments were conducted on sunny days with an average outdoor air temperature above 30°C ($\sigma = 1.3171$). Windows were equipped with interior shading devices to minimize solar radiation entering the room.

The floor standing split-type air conditioning unit was installed in the southeast corner of the room, with an outlet air velocity of approximately 3 m/s and a supply angle directed downward at around 30°. A table measuring 3.5 m × 1.6 m was placed in the room to accommodate measuring instruments and facilitate subject observation (Fig. 2a).

2.2 Participants

A total of 12 healthy subjects (6 males and 6 females), aged 19 - 23 years, participated in the experiment. All participants were native to or had resided in Jiaozuo, China, for at least one year, ensuring acclimatization to the regional hot-summer climate. None of the participants reported a history of cardiovascular, respiratory, or dermatological disorders that could affect

thermoregulation. Basic demographic information is presented in Table 1. Prior to the study, informed consent was obtained from all participants, and ethical approval was granted by the Medical Ethics Committee of Henan Polytechnic University (Approval No. HPULLSC2025-003). While the sample was homogeneous in age and regional background, this choice minimized confounding from inter-individual acclimatization differences but may limit the generalizability of the findings.

Table 1 Basic information of experimental subjects

Sex	Age	Height (cm)	Weight (kg)
Male (n = 6)	21 ± 0.6	175.2 ± 6.9	77.8 ± 14.5
Female (n = 6)	21.5 ± 1.8	162.7 ± 4.1	56.3 ± 3.3
Total (n = 12)	21.3 ± 1.3	168.9 ± 8.5	67.0 ± 15.0

To ensure that the thermal resistance of the subjects' clothing remains within this range and to minimize the impact of clothing thermal resistance on the experimental results, subjects are required to wear uniform clothing (underwear, short-sleeved shirts, shorts, and slippers). The office chairs are wooden seats with an additional clothing thermal resistance of 0.01 clo, resulting in a total clothing thermal resistance of 0.27 clo for the subjects^[42]. Throughout the experiments, participants remained seated and were permitted to read or engage in other low-intensity leisure activities. The metabolic rate was controlled and estimated at 1.0 met.

2.3 Experimental design

Based on the survey results (Appendix A), we controlled the indoor air temperature between 29.5 and 32 °C during the preparation phase. Regarding the setting of air conditioning temperature, we selected three set-points in our experiment: 28 °C (representing a warm set-point and low cold exposure), 26 °C (conventional set-point and moderate cold exposure), and 20 °C (representing a cold set-point and high cold exposure). Although the 20 °C set-point is used less frequently, it reflects extreme preferences and high energy consumption behavior. Different set temperatures generate distinct cooling profiles in terms of stimulus intensity, temperature drop rate, and compressor runtime, effectively simulating three common modes of air-conditioner use in real-life settings — low, moderate, and high cooling. In this study, the magnitude and rate of temperature decrease can be integrated into a single concept, referred to as “Thermal Stimulus Intensity (TSI)”, which captures the instantaneous strength of the cooling stimulus. When coupled with the duration of exposure, this framework evolves into a “Cumulative Thermal Stimulus Intensity (CTSI)”, reflecting the time-integrated burden of cold stress on the human body.

The experiment tested four subjects at a time, with two staff members randomly seated in the two remaining empty seats (Fig. 2b). To minimize measurement errors due to spatial non-uniformity and enhance the representativeness and robustness of the data, each subject was required to participate at different locations, ensuring coverage of temperature variation characteristics in both horizontal and vertical directions. As a result, each subject completed three experimental conditions at three different locations (measurement points 1 or 2, 3 or 4, 5 or 6), leading to a total of nine experiments. To eliminate potential bias from the experimental sequence, the order of conditions was randomized using a Latin-square design, ensuring the independence and reliability of the results. The specific effects of spatial thermal non-uniformity on human responses have been addressed in a separate study. The present research focuses instead on the temporal characteristics of human responses to varying cold exposure intensities under non-steady-state conditions.

2.4 Procedure

The entire experiment, lasting 2 hours and 30 minutes, was divided into three phases (Fig. 2c). The first phase, the preparation phase (-30 - 0 min), involved subjects sitting in a stable thermal environment of 30.5 °C to acclimatize with the environment. During this time, skin temperature sensors were installed, and the instruments were initiated. The second phase, the air conditioning operation phase (0 - 70 min), began when the air conditioning was turned on and the target temperature was set. To capture the subjective response changes during the rapid temperature drop in the first 30 minutes, subjective questionnaires were administered every 5 minutes. As the temperature began to stabilize during the subsequent 40 minutes, the interval for questionnaire responses was extended to every 10 minutes. Blood pressure and heart rate were measured every 10 minutes throughout this phase to ensure accuracy and minimize interference. The third phase, the air conditioning off phase (70 - 120 min), began when the air conditioner was turned off. During this phase, the indoor temperature increased rapidly, but at a slower rate. To match the rhythm of the changing thermal environment, subjective thermal responses were collected every 10 minutes for the first 20 minutes, then every 15 minutes for the final 30 minutes. Blood pressure and heart rate measurements followed the same rhythm.

Throughout the experiment, all subjects remained sedentary, were not informed of the set temperature, and the air conditioning control panel was covered to avoid interference from psychological expectations prevent psychological expectations from influencing the results. Each subject completed the subjective questionnaire 15 times, and indoor environmental parameters were recorded continuously at 1-minute intervals, resulting in a total of 1,620

complete data sets.

2.5 Experimental data collection

To investigate the temporal characteristics of indoor thermal environment parameters under intermittent cooling, four measurement points were arranged horizontally within the experimental room to monitor spatial variations over time. At each horizontal point, three vertical measurement levels were established at heights of 0.1 m, 0.6 m, and 1.1 m, resulting in a total of 18 measurement positions (Fig. 2d). The specifications, including measurement range and accuracy for each device, are provided in Table 2.

Table 2. Measured range and accuracy of the instrument.

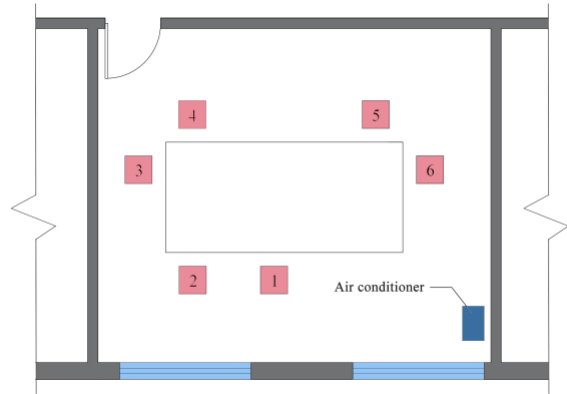
Instrument	Test content	Valid range	Accuracy
L95-2 temperature and humidity data logger (Hangzhou Luger Technology Co.)	$T_{a\text{ in}}$ RH_{in}	-10 - +60 °C 0 - 100 %	± 0.3 °C ± 5.0 %
WFWZY-1 air velocity data logger (Beijing Tianjian Huayi Technology Development Co.)	V_a	0.05 - 30 m/s	± 5.0 %
JTR04 globe thermometer (Beijing Century Jiantong Technology Co.)	T_g	5 - 120 °C	± 0.5 °C
JTR08ZO wireless outdoor temperature and humidity data logger (Beijing Century Jiantong Technology Co.)	$T_{a\text{ out}}$ RH_{out}	-40 - 85 °C 0 - 100 %	± 0.3 °C ± 5.0 %

Subjective responses were collected using an electronic questionnaire, which included basic demographic information and subjective evaluations of the thermal environment specifically thermal sensation, thermal comfort, and thermal acceptability. Thermal sensation and comfort were assessed using a 7-point scale, while thermal acceptability was measured on a 4-point scale. Detailed descriptions of each scale are provided in Appendix B.

For skin temperature measurement, previous studies have demonstrated that using seven or more sites including the hands and feet can achieve over 95.0 % agreement with the mean of 10,841 full-body skin temperature measurements, ensuring high reliability. Accordingly, this experiment adopted a 7-point measurement method, covering the forehead, chest, forearm, back of the hand, thigh, calf, and ankle. Skin temperatures were continuously monitored using iButton recorders (DS1922L, Wdsen Electronic Technology Co., Ltd). Measured sites and average skin temperatures were calculated in Appendix B.

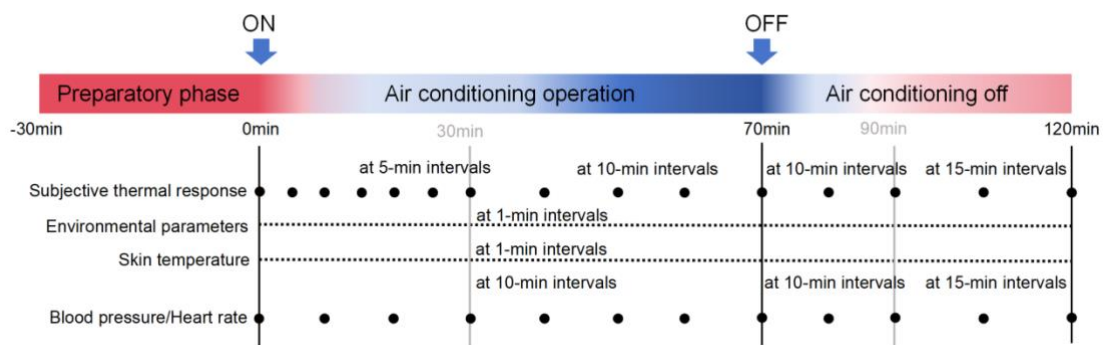
Blood pressure and heart rate were measured using a OMRON electronic sphygmomanometer (T10, Omron Co., Ltd.) placed on the left wrist. The palm was positioned upward, and the cuff was wrapped 1 - 2 cm above the wrist bone, aligned with heart level to

ensure measurement accuracy. During the measurement, participants remained seated in a relaxed, quiet, and motionless state. The procedure is illustrated in Fig. 2e.



a. Experimental site

b. Floor plan of the laboratory room



c. Experimental procedure



d. Environmental parameter acquisition



e. Physiological parameter collection

Fig. 2 Overview of the experimental setup and procedure.

The figure illustrates the physical layout, time-structured procedure, and synchronized collection of environmental and physiological data, forming the basis for analyzing human responses to dynamic thermal stimuli.

2.6 Data analysis

We performed statistical analyses using SPSS (IBM SPSS Statistics 26 IBM Corp., Armonk, NY, USA). Data normality was assessed with the Shapiro-Wilk test. As the distributions were found to be non-normal, the Friedman test was applied for non-parametric comparisons. We also used Spearman's rank correlation to examine relationships among variables.

We used means and standard errors of the mean (SEM) to observe the characteristics of subjective and physiological responses, and calculated standard deviations (SD) to assess variability. In this study, the stabilization times of indoor air temperature, skin temperature, and psychological responses (i.e., thermal sensation, thermal comfort, and thermal acceptability) were identified based on the rate of change method.

$$R_{T_a} = \Delta T_a / \Delta t$$

$$R_{T_{skin}} = \Delta T_{skin} / \Delta t$$

$$R_{vote} = \Delta Vote / \Delta t$$

R_{T_a} : Rate of temperature change in Air; $R_{T_{skin}}$: Rate of change in skin temperature

R_{vote} : Rate of change in subject voting

ΔT_a : Adjacent air temperature difference; ΔT_{skin} : Adjacent mean skin temperatures difference; $\Delta vote$: Adjacent subjective voting difference; Δt : time interval.

Based on the methods for determining stability time in existing studies on dynamic thermal comfort, this study adopted the rate change method. In the studies by Jiang et al.^[37], and Yang et al.^[38], and Yang et al.^[39] stability was defined based on the response rate approaching 0 rather than reaching an absolute constant value. In the studies, thresholds were empirically determined using their own datasets (e.g., ± 0.01 or ± 0.02 °C/min), but the specific thresholds were not fixed and depended on the range of fluctuations observed under specific experimental conditions. In this study, based on the actual change amplitude observed during the quasi-steady-state plateau phase, ± 0.02 °C/min was selected as the threshold for air and skin temperature, and ± 0.1 votes/min as the threshold for subjective sensation.

3 Results

Among the environmental parameters monitored in this study, air temperature was identified as the factor with the greatest influence on thermal physiology and perceived responses. Although air velocity and relative humidity were also measured, the range of

variation for these parameters was relatively limited under experimental conditions, and no consistent correlation with response variables was observed. Therefore, the analysis in the following sections focuses primarily on air temperature, as it best represents the dynamic characteristics of the indoor thermal environment under intermittent cooling.

3.1 Air-conditioning operation phase

3.1.1 Air temperature

Fig. 3a illustrates the air temperature profiles and the corresponding change rates under three set temperature conditions. During the initial phase of the experiment (0 - 5 min), air temperatures in all conditions declined rapidly from the initial 30.5 °C, with change rates approaching -0.4 °C/min. The Friedman test revealed no significant differences among the three-temperature set-point groups ($p > .05$). These results indicate that the initial cooling rate was not significantly affected by the set temperature, suggesting that the common practice of lowering the set-point to achieve faster cooling may be ineffective under the tested conditions.

After 5 minutes of operation, distinct differences in temperature trajectories emerged among the three conditions. The air temperature in the low cooling exposure (LCE) group (low cold exposure, 28 °C) stabilized within 10 minutes, while stabilization in the medium cooling exposure (MCE) group (moderate cold exposure, 26 °C) occurred after approximately 15 minutes. In contrast, the high cooling exposure (HCE) group (high cold exposure, 20 °C) exhibited a continuous temperature decline throughout the 70-minute cooling phase, without reaching the set-point. These findings suggest that lower set temperatures are associated with higher cooling intensity and longer duration of thermal instability, resulting in extended exposure to non-steady-state cold conditions.

Overall, the dynamic characteristics of air temperature under intermittent cooling were evident in both the cold exposure intensity and the time required to reach stabilization. These two dimensions jointly define the level of accumulated cold exposure, which serves as a key external input influencing the timing and pattern of physiological and perceptual thermal responses. In the following sections, we explore how this compound environmental dynamic influences physiological regulation and perceptual adaptation.

3.1.2 Physiological response

Fig. 3b and 3c illustrate the differences in physiological response during the air conditioning operation phase under varying temperature change rates.

In the HCE condition (high cold exposure, 20 °C), skin temperature declined continuously without reaching stabilization, with a maximum drop of 3.5 °C. Its rate of decrease was

significantly higher than that in the other groups ($p < .05$). Systolic blood pressure (SBP) remained stable ($p > .05$), while diastolic blood pressure (DBP) showed a significant increase after 30 minutes, reaching a peak of 67.3 mmHg, an increase of +6.9 mmHg ($p < .05$), and a total change of +10.2 mmHg throughout the entire experimental period. Heart rate gradually decreased throughout the exposure period, with a maximum reduction of 10.2 bpm, showing the largest magnitude of change among the three conditions. These findings suggest that at lower set temperatures, the body requires stronger physiological regulation to maintain homeostasis, resulting in higher physiological burden. In the MCE condition (moderate cold exposure, 26 °C), skin temperature decreased initially and stabilized after approximately 20 minutes, with a total drop of 1.4 °C. SBP showed no significant change ($p > .05$), while DBP slightly increased after 30 minutes, but the increase was significantly smaller than that in the HCE group ($p < .05$). Heart rate remained relatively stable throughout the cooling period ($p > .05$). These results indicate that subjects adapted more quickly under moderate cold exposure, and the physiological load remained within an acceptable range.

In the LCE condition (low cold exposure, 28 °C), skin temperature decreased slightly by 1.1 °C and stabilized after 15 minutes of air conditioning operation. There were no significant fluctuations in systolic blood pressure (SBP), diastolic blood pressure (DBP), or heart rate ($p > .05$), indicating minimal disturbance to the physiological system. The rapid stabilization of all indicators suggests high adaptability to the mild cooling.

In summary, the rate of temperature change substantially influences both the magnitude of physiological responses and the time required for stabilization. The HCE condition induced stronger and more prolonged physiological fluctuations, while the MCE and LCE conditions were more effective in maintaining thermal and cardiovascular stability. Therefore, cooling intensity, encompassing both the target temperature and the rate of change, serves as a key external driver of physiological response under cold exposure, providing a foundation for further understanding of thermoregulatory mechanisms in non-steady thermal environments.

3.1.3 Subjective thermal response

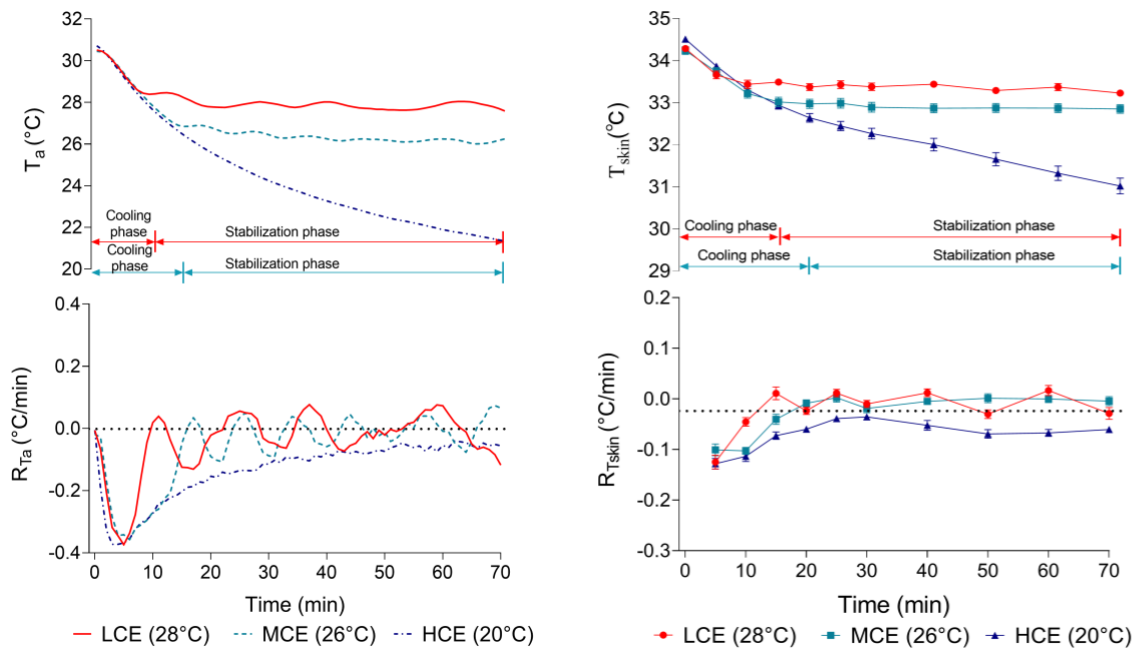
Fig. 3d illustrates the trends in subjective thermal responses under different temperature change rates during the air-conditioning operation phase. Thermal sensation, thermal comfort, and thermal acceptability showed significant differences among the three set-point conditions ($p < .001$). However, during the initial 20 minutes of cooling, thermal comfort and thermal acceptability exhibited similar improvement trends across all three cold exposure intensities — LCE (low cooling exposure, 28 °C), MCE (moderate cooling exposure, 26 °C), and HCE

(high cooling exposure, 20 °C). Participants' evaluations generally shifted from "slightly uncomfortable" or "slightly unacceptable" toward "comfortable" and "acceptable," indicating similar perceptual responses to environmental change regardless of cooling intensity. In terms of thermal sensation, all three groups experienced a significant decrease within the first 5 minutes, rapidly dropping from "warm" to "slightly warm." By the 20th minute, the groups gradually converged, entering the temperature ranges of "slightly warm," "neutral," and "slightly cool." Despite differences in environmental parameters, subjective thermal responses remained relatively similar among the three conditions during this period, suggesting that perceptual patterns did not diverge substantially in the early stage of cold exposure.

After 20 minutes, thermal sensation continued to decline in the HCE condition (high cooling exposure, 20 °C) without reaching a steady state, reaching cool sensation at the end of the 70 min exposure. Thermal comfort and thermal acceptability initially improve from "slightly uncomfortable" and "slightly comfortable" to "comfortable" and "acceptable" during the first 20 minutes, both metrics declined gradually as a result of over-cooling, ended at neutral level, again failing to stabilize by the end of the experiment. This suggests that initial cooling may provide temporary relief, but prolonged exposure to high levels of cold exposure can lead to discomfort and reduced acceptability in later stages.

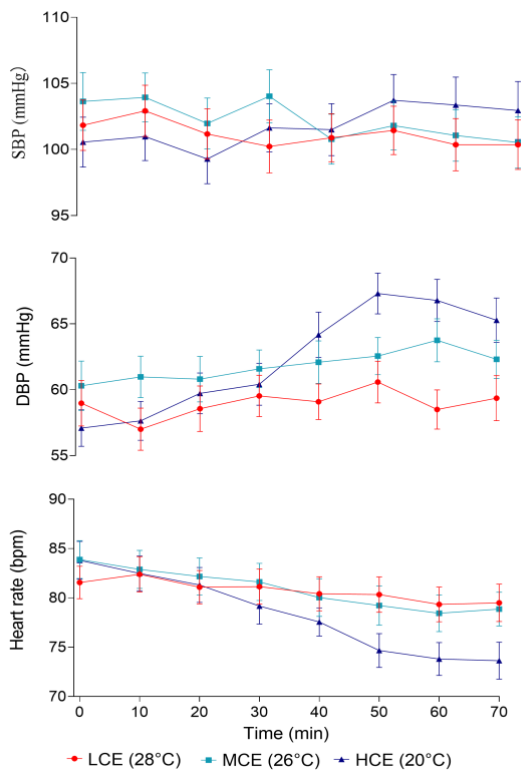
In the MCE condition (moderate cooling exposure, 26 °C), after the 20 minutes, thermal sensation continued to decline, but at a much slower rate compared to the HCE group, stabilizing in 40-minute mark. By the end of the 70-minute exposure, the thermal sensation shifted from "neutral" to "slightly cool" sensation. In contrast, both thermal comfort and thermal acceptability in the MCE group rapidly improved during the first 20 minutes and then remained stable, maintaining levels of "slightly comfortable" and "slightly acceptable" throughout the remainder of the exposure. This pattern, as shown in the figure, indicates that under moderate cooling intensity, the human body achieves and sustains a stable state of moderate comfort and acceptability soon after initial adaptation, rather than continuing to improve or deteriorate over time. In the LCE condition (low cooling exposure, 28 °C), subjective thermal responses demonstrated remarkable stability after the initial 20 minutes. Thermal sensation stabilized within 20 minutes at a level slightly above neutral and remained nearly unchanged throughout the remainder of the exposure. Both thermal comfort and acceptability reached their highest values among all conditions within the first 20 minutes and then maintained or even slightly increased these favorable levels until the end of the test. This pattern suggests that low-intensity cooling induces minimal thermal disruption, allowing subjects to maintain consistent high and stable thermal comfort and acceptability during

prolonged exposure.

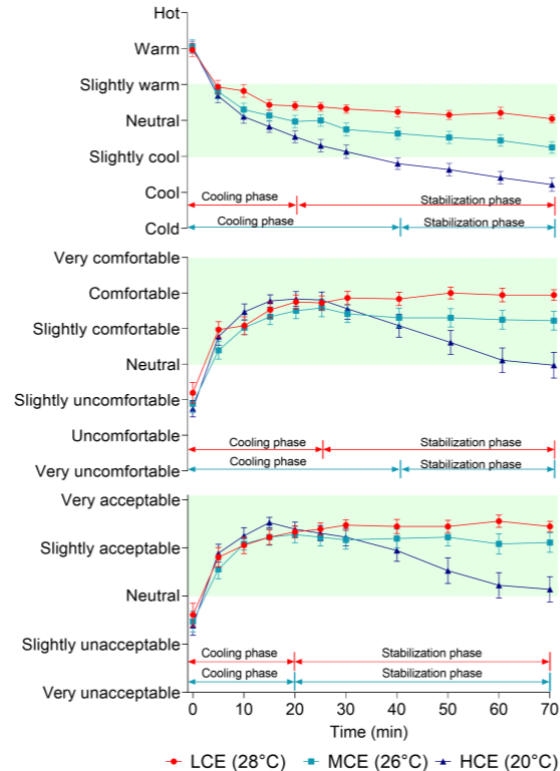


a. Air temperature and rate of change

b. Skin temperature and rate of change



c. Blood pressure and heart rate



d. Subjective thermal response

Fig. 3 Temporal evolution of Air Temperature, physiological responses, and subjective thermal perceptions under three cooling intensity conditions (LCE: 28 °C, MCE: 26 °C, HCE: 20 °C) during the air-conditioning operation phase.

All variables are shown as mean \pm SEM, while the volatility analysis is based on SD. Sample sizes differ across parameters due to varying measurement intervals, as described in the Methods section. The cooling phase refers to the period immediately following the activation of air conditioning, during which air temperature, physiological responses, and subjective perceptions change rapidly

in response to the sudden environmental change. The stabilization phase begins after a certain duration, when these variables stabilize and remain statistically steady values. The green area in the figure represents the comfortable and acceptable range. Colored arrows indicate the duration of each phase under different cooling intensities: Red arrows represent the cooling and stabilization periods under LCE (28 °C); Light blue arrows represent MCE (26 °C); No stabilization arrow is shown for HCE (20 °C), as the system did not reach a steady state during the exposure period due to persistent temperature decline. These graphs collectively demonstrate that higher cooling intensity leads to greater thermal instability, prolonged physiological disturbance, and delayed perceptual adaptation.

In summary, subjective thermal responses exhibited a typical pattern of initial fluctuation followed by stabilization, closely modulated by cooling intensity. Higher cooling intensities delayed stabilization and were more likely to induce perceptual discomfort, while low to moderate intensities facilitated rapid adaptation and sustained comfort. These observations underscore the importance of moderating cooling dynamics to maintain thermal satisfaction in real world scenarios.

3.2. Air conditioning off phase

3.2.1 Air temperature

The recovery phase was monitored over 50 minutes following air-conditioning shutdown. Fig. 4a shows the rewarming profiles and temperature change rates (R_{Ta}) across the three cooling conditions during the recovery phase (70 - 120 min). A Friedman test indicated significant differences among the three conditions ($p < .05$).

In the initial 10 minutes, all groups exhibited temperature recovery. However, the rate of rewarming and the stabilization time differed markedly: The HCE condition, showed rapid initial temperature increase ($R_{Ta} \approx +0.48$ °C/min), but failed to stabilize within 50 minutes, exhibiting the larger residual variance ($\sigma = 2.27$ °C, $p < .05$). The MCE condition achieved stabilization after approximately 35 minutes. The LCE condition reached a stable state most rapidly (within 30 minutes), and showed the lowest residual variance ($\sigma = 0.82$ °C).

These results indicate that stronger cold exposure significantly delays environmental recovery and increase thermal inertia instability, likely due to enhanced thermal inertia and greater residual cooling retained indoor surfaces and air mass. The prolonged thermal non-uniformity observed in the HCE condition creates an unstable thermal background that may act as a latent stress and potentially influencing subsequent comfort recovery and physiological regulation as explored in the following sections.

3.2.2 Physiological response

Fig. 4b and 4c illustrate the temporal dynamics of skin temperature, blood pressure, and heart rate under different cooling exposure.

In the HCE group, skin temperature exhibited the most substantial rebound, increasing by 2.2 °C within the first 30 minutes after the air conditioner was turned off. The rate of increase was significantly higher than in the other groups ($p < .05$), and stabilization was only achieved

after about 35 minutes (105 min), highlighting a delayed return to thermal equilibrium. Diastolic blood pressure (DBP) remained elevated compared to MCE and LCE throughout the recovery phase, with the inter-group difference peaking at 5.9 mmHg ($p < .05$), reflecting persistent vasoconstriction activity and heightened cardiovascular strain. Systolic blood pressure (SBP) showed no significant variation ($p > .05$). Additionally, heart rate in the HCE group remained 5 - 8 % lower than in the other groups ($p < .05$), indicating sustained autonomic modulation and incomplete cardiovascular recovery. The combination of persistently elevated DBP and suppressed heart rate underscores a prolonged period of physiological disturbance and delayed homeostatic restoration following high-intensity cold exposure. In the MCE group, skin temperature increased steadily by 1.0 °C and reached a stable plateau at around 35 minutes. DBP exhibited a modest increase (1.5 mmHg), which was significantly less pronounced than in the HCE group ($p < .05$), while SBP remained unchanged. Heart rate remained minimal fluctuation and remained stable throughout the recovery phase ($p > .05$). These results indicate that moderate cooling exposure enables a more balanced and efficient thermoregulation and cardiovascular recovery, with both thermal and circulatory parameters returning smoothly to baseline. In the LCE group, skin temperature rebounded minimally (0.8 °C) and stabilized most rapidly within 35 minutes, closely paralleling the baseline level. Both SBP and DBP exhibited no significant changes ($p > .05$), and heart rate remained stable as well, indicating that low level cold exposure caused minimal physiological disruption and allowed for rapid homeostatic restoration.

In summary, the intensity of cold stimulation has a significant impact on the trend and magnitude of physiological recovery. Higher cold stimulation intensity triggers a stronger rebound response in skin temperature, prolongs the duration of elevated diastolic blood pressure, and causes a delay in heart rate recovery. Conversely, moderate and weaker cold loads facilitate a smoother recovery process, emphasizing the importance of controlling the intensity of cold exposure in intermittent cooling strategies.

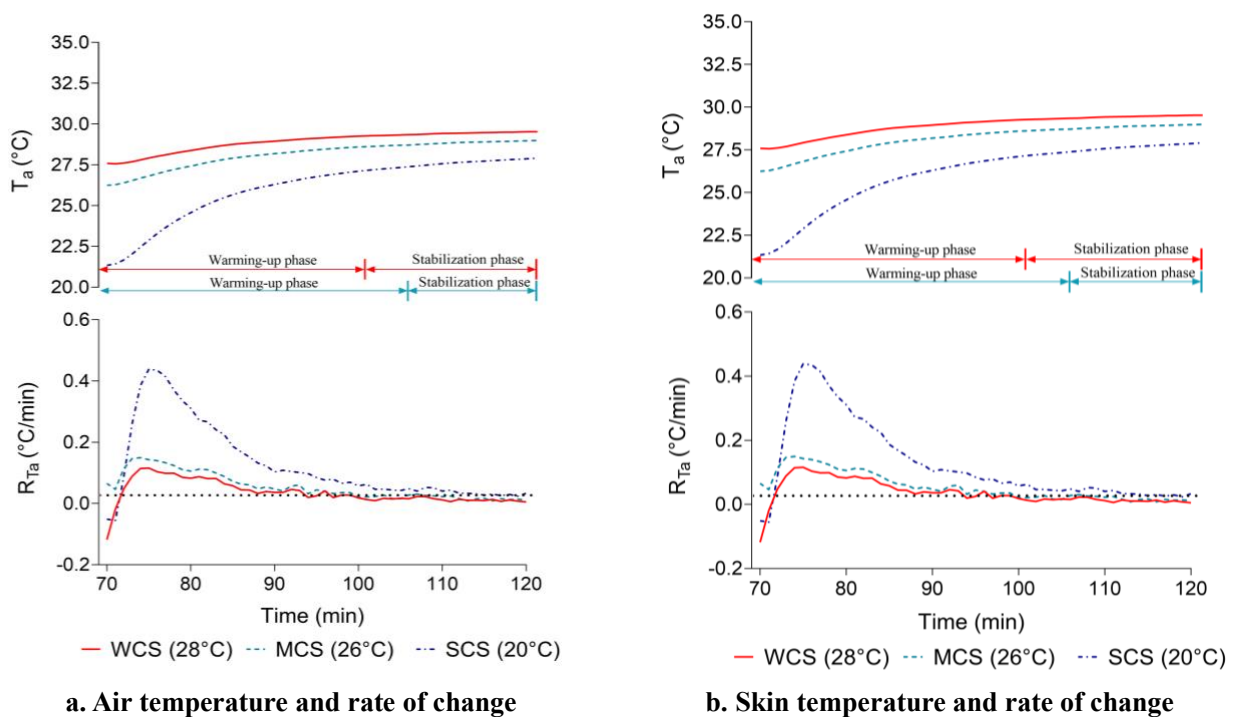
3.2.3 Subjective thermal response

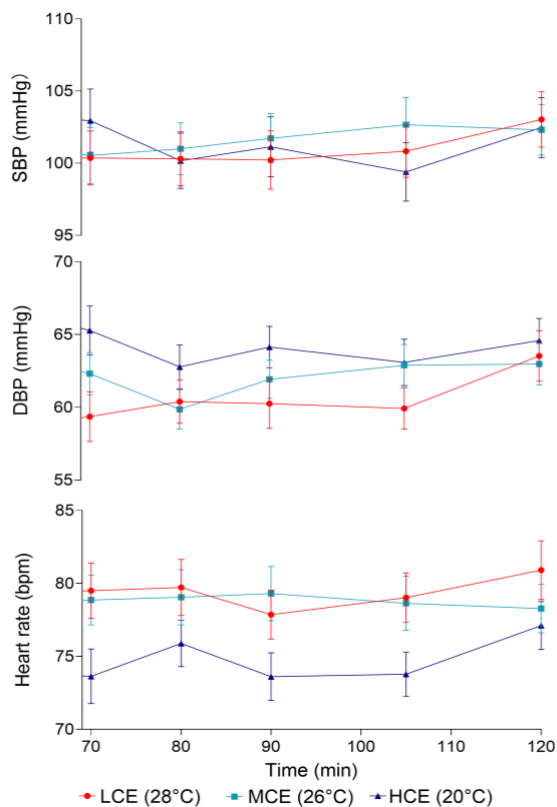
Fig. 4d show the trends in thermal sensation, comfort, and acceptability during the air-conditioning off phase across the three cooling conditions. Significant differences were found among the conditions ($p < .001$).

In the HCE condition, thermal sensation increased rapidly from “cool” to “neutral” within the first 20 minutes after the air conditioner was turned off, and stabilized at this level around 35 minutes (105 min). Both thermal comfort and thermal acceptability improved markedly

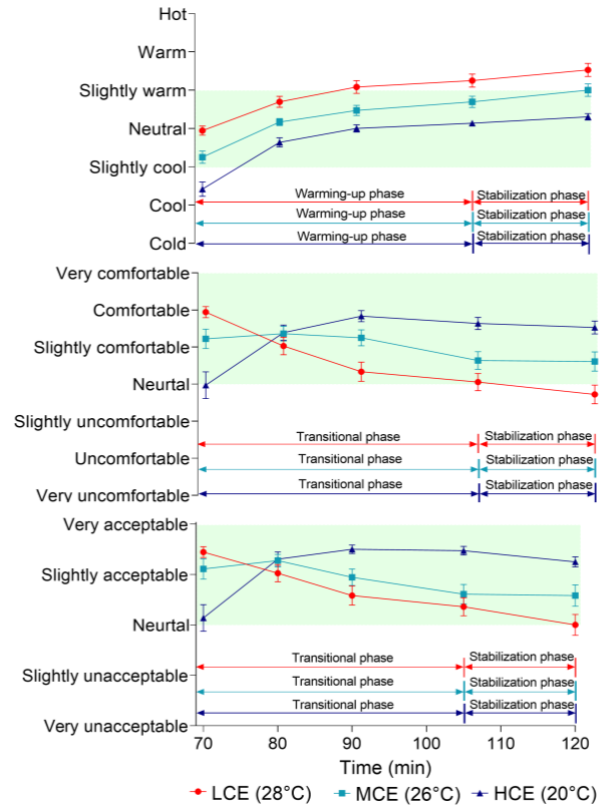
during the initial 20 minutes, reaching “comfortable” and “slightly acceptable”, and then remained stable at the highest levels among all three conditions throughout the remainder of the recovery phase. In both the MCE and LCE conditions, thermal comfort and acceptability stabilized at around 35 minutes after air-conditioning shutdown, consistent with the stabilization time observed in the HCE group. However, unlike the HCE condition, neither group exhibited improvement in comfort or acceptability during the recovery phase. For the MCE condition, both thermal comfort and acceptability remained relatively steady after stabilization, maintaining levels around “slightly comfortable” and “slightly acceptable.” In contrast, in the LCE condition, comfort and acceptability gradually declined over time, despite the continued warming of the environment.

These findings demonstrate that while all three conditions achieved thermal stabilization at a consistent time point of approximately 35 minutes after air-conditioning shutdown, the direction, magnitude, and quality of subjective thermal responses during recovery were distinctly modulated by the preceding cold exposure intensity.





c. Blood pressure and heart rate



d. Subjective thermal response

Fig. 4 Thermal and physiological recovery patterns during the air-conditioning off phase under three cooling conditions (LCE: 28 °C, MCE: 26 °C, HCE: 20 °C).

All variables are presented as mean ± SEM. Sample sizes may differ across parameters due to varying measurement intervals, as detailed in the Methods section.

For definitions of the warming-up and stabilization phases, and the meaning of colored arrows, see the caption of Fig. 3.

4 Discussions and limitations

4.1 Thermal Response Characteristics under Intermittent Cooling

Table 3 summarizes the stabilization times and reaction characteristics of key physiological and subjective parameters under different cooling intensities, providing a comprehensive overview of the dynamic thermal responses observed in this study. The result reveals the non-steady-state characteristics of thermal responses in intermittent cooling environments. During the initial air-conditioning operation (0 - 5 min), all conditions exhibited rapid temperature decline (maximum $R_{Ta} = -0.4 \text{ }^\circ\text{C}/\text{min}$), consistent with the refrigeration system startup characteristics reported by Li et al.^[43] Notably, within the first 20 minutes after air-conditioning activation, the dynamic changes in thermal responses including skin temperature, thermal sensation, and comfort, are highly similar across all cooling intensity conditions, with minimal differences between groups. This pattern is consistent with previous studies showing that both skin temperature and thermal sensation tend to reach a steady level

within about 20 minutes following a step change in ambient temperature, and that differences among conditions become more pronounced only after this initial adaptation period^[44]. The key difference lies in the decisive role of cooling stimulus intensity on subsequent thermal environmental stability: the LCE and MCE groups achieved steady state within 10 - 15 minutes, while the HCE group failed to stabilize due to continuous temperature decline. After air-conditioning shutdown, the HCE group exhibited significant “temperature hysteresis effects” — the fastest temperature recovery rate (+0.48 °C/min) but the largest fluctuation amplitude ($\sigma = 2.27$ °C), without achieving steady state. In contrast, the LCE and MCE groups reached stability within 30 - 35 minutes. This indicates that intense cold exposure significantly prolongs environmental recovery time through building thermal inertia^[45].

Table 3. Stabilization Time and Response Characteristics under Different Cooling Conditions

Parameter	Phase	HCE (20 °C) /min	MCE (26 °C) /min	LCE (28 °C) /min	Hysteresis (VS Ta)	Reaction Characteristics
Ta		/	15	10	/	Rapid decline within 0 - 5 min; HCE group did not reach steady state.
Tskin		/	20	15	√	The HCE group continued to decline, while the LCE/MCE group tended to stabilize.
Blood pressure	AC on	/	/	/	/	The change was stable, and the DBP in the HCE group increased after 30 minutes.
Heart beat		/	/	/	/	The change is stable, with the HCE group continuing to decline.
Thermal sensation		/	40	20	√	The HCE group did not reach steady state, while the LCE/MCE group tended toward stability.
Thermal comfort		/	40	25	√	Comfort decreased in the HCE group in the later stages, while it remained stable in the LCE/MCE groups.
Thermal acceptability		/	20	20	√	
Ta		/	35	30	/	The HCE group did not reach steady state, while the LCE/MCE group tended toward stability.
Tskin		35	35	35	√	All three groups tended to stabilize, with the HCE group showing the largest rebound.
Blood pressure	AC off	/	/	/	/	HCE group had higher DBP than LCE/MCE group.
Heart beat		/	/	/	/	HCE group shows lowest values.
Thermal sensation		35	35	35	√	
Thermal comfort		35	35	35	√	All groups stabilize at 35 minutes.
Thermal acceptability		35	35	35	√	

Notes: “/” indicates that stabilization was not reached during the observation period. “√” indicates hysteresis (lag) compared to air temperature. DBP: Diastolic Blood Pressure. This table integrates both the stabilization times and the qualitative response characteristics for each parameter, phase, and cooling intensity, as

requested.

At the physiological response level, different cooling stimulus intensities resulted in significant differences in regulatory efficiency. During the air conditioning operation phase, The LCE and MCE groups showed skin temperature stabilization within 15 - 20 minutes with mild cardiovascular parameter fluctuations, while the HCE group exhibited continuous skin temperature decline, significant diastolic blood pressure elevation (+8.2 mmHg, $p < .05$), and heart rate suppression, confirming that intense cold stimulation triggers cumulative physiological load^[46]. The recovery phase after air-conditioning shutdown further revealed non-linear characteristics: the HCE group showed the largest skin temperature rebound amplitude ($\Delta T = 2.2$ °C) with persistently elevated diastolic blood pressure, confirming that physiological recovery is jointly regulated by prior cold exposure intensity and duration^[47].

Subjective thermal responses demonstrated a universal 35-minute recovery window. During air-conditioning operation, the HCE group exhibited an “early relief — late deterioration” phase change, while the LCE and MCE groups stabilized within 20 - 40 minutes. After air-conditioning shutdown, all subjective indicators synchronized and stabilized at approximately 35 minutes (synchronous with skin temperature changes), but the final comfort state depended on prior cold exposure intensity: the HCE group recovered to optimal comfort levels, while the LCE group experienced comfort decline during environmental warming.

This study breaks through traditional steady-state thermal comfort frameworks^{[48][49]} and discovers asymmetric dynamic response patterns in intermittent cooling scenarios: cooling exposure intensity not only affects regulatory speed but also determines the final state of thermal perception during recovery (such as high comfort in the HCE group versus comfort attenuation in the LCE group), surpassing linear models of temperature step changes^[50] or ramp changes^[51]. By integrating the temporal dimension, this study proposes an innovative model of “cooling exposure intensity duration” jointly driving physiological load accumulation (Fig. 5), addressing the limitations of existing dynamic thermal models that focus solely on temperature parameters^[52]. At the application level, the revealed 35-minute thermal perception recovery window provides a critical time threshold for intermittent cooling system design, better aligning with human dynamic adaptation processes compared to traditional continuous cooling^[53].

By quantifying the coupling effects of cooling stimulus intensity, rate, and time, this study establishes a non-steady-state thermal adaptation theoretical framework for intermittent cooling environments, providing physiological evidence for dynamic air-conditioning control strategies and filling the research gap in non-steady-state thermal comfort theory for

intermittent cooling scenarios.

4.2 Coupling Effect of Cooling Intensity and Exposure Duration

(1) Dominant Role of Cooling Intensity

The dominant role of cooling intensity is evident in how it directly determines the severity of the initial physiological response. For example, strong cold exposure at 20 °C rapidly activates the sympathetic nervous system, leading to a cascade of physiological reactions: peripheral vasoconstriction reduces skin blood flow, diastolic blood pressure rises significantly ($\Delta\text{DBP} > 5.9$ mmHg) and heart rate remains suppressed, while core body temperature is maintained through defensive mechanisms^[54]. Such intense cold stimuli not only alter environmental parameters, but also reshape the temporal sequence of physiological regulation. This results in differentiated response patterns under different cooling intensities, such as the continuous decline of skin temperature in the HCE group compared to the rapid stabilization observed in the LCE group.

(2) Cumulative Effect of Exposure Duration

As the duration of cold exposure extends beyond 20 minutes, the physiological response evolves in a phased manner. During the rapid cooling phase (0 - 20 minutes), the response is dominated by fast compensatory regulation of skin temperature. Once exposure continues beyond 20 minutes, the response gradually shifts to deeper physiological systems, as seen in enhanced cardiovascular compensation (such as sustained elevation of diastolic blood pressure in the HCE group) and delayed heart rate recovery (with heart rate suppression persisting up to 70 minutes in the HCE group). In addition, a phase-dependent relationship between physiological and psychological responses is observed: in the HCE group, as skin temperature continues to decrease, subjective thermal comfort first improves from heat discomfort to comfort, but then declines again as heat loss accumulates. This reflects a dynamic shift in the dominant physiological factors influencing thermal perception at different stages of cold exposure. Such time-dependent patterns are also supported by Bai et al.^[55], who found that cardiovascular parameters may continue to lag behind even after environmental conditions have returned to normal.

(3) Synergistic Effect of Cooling Intensity and Exposure Duration

When high cooling intensity is combined with prolonged exposure, as in the 70-minute HCE group, a synergistic amplification effect occurs. This combination can exceed the body's compensatory threshold for thermoregulation^[46], resulting in continuous skin temperature decline without stabilization. The cumulative load is further reflected in increased fluctuations

of cardiovascular parameters (elevated diastolic blood pressure and reduced heart rate) and a biphasic pattern of subjective comfort, characterized by initial relief followed by subsequent deterioration. Moreover, during the recovery phase after cooling ends, the HCE group exhibits the largest rebound in skin temperature ($\Delta T = 2.2$ °C) and persistently elevated diastolic blood pressure, indicating that intense cold exposure can induce profound and lasting physiological changes.

4.3 Limitations of the PMV Model in Intermittent Cooling Environments

To evaluate the applicability of the PMV model under intermittent air conditioning conditions, we compared its predictions with actual Thermal Sensation Voting (TSV) data at different cooling intensities using the CBE thermal comfort tool^[56] (Figure 5). At LCE (28 °C), PMV accuracy was 66.7%, with significant overestimation of TSV at 40 - 80 minutes ($p < .05$), though the discrepancy diminished after shutdown. At MCE (26 °C), accuracy was also 66.7%, with overestimation occurring between 70 - 105 minutes, but it performed better during the cooling phase compared to LCE (91.0% vs. 63.6%). At HCE (20 °C, accuracy was only 33.3%, with persistent underestimation between 20 and 90 minutes and overestimation between 105 and 120 minutes. The results indicate that the steady-state assumption of PMV has limitations under dynamic cooling conditions, consistent with findings from existing studies^{[57][58]}

The difference between PMV and TSV can be explained by thermophysiological mechanisms. PMV is based on the assumption that the human body is in thermal equilibrium with the environment^[59], whereas intermittent cooling places the body in a state of non-steady-state regulation. PMV values are calculated directly from environmental parameters, as it assumes an individual's thermal sensation is a passive response—a function of physiological strain imposed by the environment—without elucidating how people physiologically and subjectively react to thermal conditions^{[59][60]}. During air conditioning operation, air temperature drops rapidly, but subjective perception lags due to vasoconstriction and delayed thermoregulation, causing PMV to underestimate cold sensation early on. After system shutdown, skin rewarming outpaces perceptual recovery, causing persistent cold sensation and PMV overestimation during recovery. The discrepancy severity depends on cold exposure intensity: HCE induces strong vasoconstriction and potential non-shivering thermogenesis to maintain thermal equilibrium^[61]. These active adjustments exceed PMV's static calculation scope, resulting in maximum and persistent errors. Conversely, under LCE and MCE with lower regulatory demands, PMV - TSV convergence improves.

Therefore, we believe that static models alone cannot reliably assess transient thermal

adaptation. A dynamic metric—such as the proposed Cumulative Thermal Stimulus Index (CTSI)—that integrates intensity and exposure duration is needed to reflect the spatiotemporal characteristics of thermoregulation and support intelligent control strategies in real-world cooling environments.

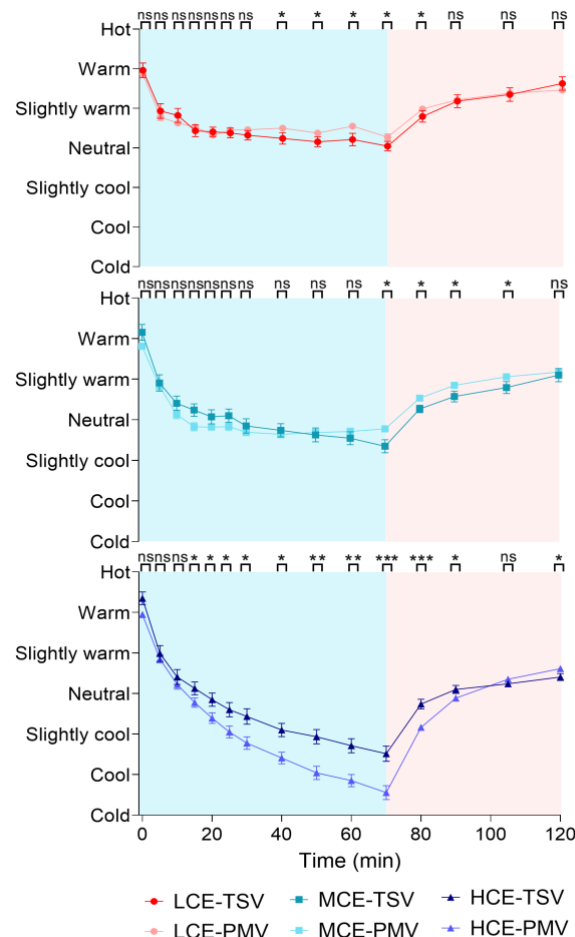


Fig. 5 Comparison of PMV and actual TSV under three conditions (LCE: 28 °C, MCE: 26 °C, HCE: 20 °C)

This figure illustrates that the interaction between cold stimulus intensity and exposure duration significantly affects the accuracy and applicability of PMV. The blue area in the diagram represents the air conditioning operation phase, while the pink area represents the air conditioning shutdown phase. As cold stimulus intensity increases and exposure duration lengthens, the deviation in PMV becomes greater.

4.4 Development of a Conceptual Framework of Cumulative Thermal Stimulus Index (CTSI)

To evaluate the combined effects of thermal stimulus intensity and exposure duration on human thermal responses in non-steady-state cooling environments, this study proposes a conceptual index — the Cumulative Thermal Stimulus Index (CTSI). This index quantifies the total thermal load (either heating or cooling) experienced by the human body by coupling temperature deviation with duration of exposure.

Using the thermal neutral temperature of 26 °C as a reference point, CTSI reflects the integrated thermal stress through the following interpretation: when the ambient temperature is above 26 °C, $\Delta T(t) > 0$, CTSI accumulates as a positive value, representing heat load buildup; when the ambient temperature is below 26 °C, $\Delta T(t) < 0$, CTSI accumulates as a negative value, representing cold load buildup; when CTSI is approximately zero, it indicates a thermally neutral state within the body's acceptable regulatory zone.

The conceptual formulation of CTSI is expressed as:

$$CTSI = \int_{t_0}^{t_1} w(t) \cdot \Delta T(t) dt$$

where $\Delta T(t)$ represents the deviation of ambient temperature from the neutral temperature (26 °C). In this study, $w(t)$ is introduced as a weighting function reflecting the body's time-dependent sensitivity to thermal exposure. This interpretation is supported by prior studies, which have demonstrated temporal dynamics such as lag and adaptation in both perceptual and physiological responses under non-steady-state environments^{Error! Reference source not found.}[63]. Established physiological indicators—including the rate of change in heart rate (dHR/dt), blood pressure, and skin temperature—have been shown to closely track heat stress and thermal comfort dynamics^{[64][65]}. Thus, in the CTSI formulation, $w(t)$ can be conceptually regarded as a function of such transient response rates, providing a foundation for future empirical parameterization. However, precise modeling of $w(t)$ remains beyond the scope of this conceptual study. Importantly, the experimental results in this study are consistent with the CTSI interpretation. When CTSI values fall below the lower bound (negative zone), subjects exhibited stronger cold sensation, lower thermal comfort, and more pronounced physiological burden, particularly under high cooling exposure (HCE). When CTSI remained close to zero (neutral zone), participants reported stable thermal sensation and comfort, with minimal physiological fluctuations, typically observed during moderate cooling exposure (MCE). When CTSI exceeded the upper bound (positive zone), thermal discomfort and fatigue symptoms were more evident, consistent with heat load accumulation during recovery. These findings provide initial empirical support for the validity and applicability of CTSI as an integrative indicator.

At this stage, CTSI is presented as a conceptual framework to emphasize the joint influence of thermal stimulus intensity \times duration on human thermophysiological and perceptual responses. Compared with traditional evaluation methods that rely solely on fixed temperature set-points or exposure duration, CTSI provides a dynamic, continuous, and physiologically meaningful measure of thermal load.

This index can potentially support: determining whether the thermal load exceeds the body's regulatory capacity; identifying the appropriate timing to activate or terminate cooling interventions; offering a quantitative foundation for smart control, adaptive adjustment, and comfort maintenance in intelligent air-conditioning systems.

Future work will focus on validating and refining this index using cardiovascular and physiological data collected in this study, with the aim of evolving CTSI from a theoretical model into a practical control tool.

4.5 Design control strategy: Intelligent cooling control framework based on CTSI

In intermittent cooling environments, the human response to thermal load follows a dynamic process of accumulation, regulation, and recovery. To enable more precise cooling control, this study introduces the Cumulative Thermal Stimulus Index (CTSI), which continuously and dynamically reflects both the magnitude of deviation from the thermal neutral point (26 °C) and the duration of exposure. CTSI serves as a real-time reference for intelligent cooling strategy adjustment.

As illustrated in the figure, positive CTSI values indicate heat load accumulation (heat exposure zone), while negative values indicate cold load accumulation (cold exposure zone). The system defines an “acceptable adjustment zone” (gray band) and continuously monitors CTSI changes. When CTSI exceeds the upper threshold, signaling excessive heat load, the system should activate or intensify cooling. When CTSI drops below the lower threshold, indicating excessive cold load, cooling should be reduced, the set-point raised, or the AC turned off to minimize cold stress. By dynamically adjusting CTSI, the system achieves balanced thermal regulation, maintaining human comfort and physiological stability within a controllable range.

Importantly, experimental results demonstrate that after each cooling reduction or AC shutdown, a recovery window of approximately 35 minutes is required for physiological and perceptual stabilization. Therefore, the control strategy should avoid frequent switching and ensure that, after each adjustment, CTSI remains within the acceptable zone for at least 35 minutes to support full recovery and prevent cumulative thermal stress. This inherent design of minimizing unnecessary compressor cycles is a key mechanism through which the CTSI-based strategy achieves its energy-saving potential, as it prioritizes sustained comfort periods over reactive, frequent adjustments.

Compared to traditional “set-point + constant operation” modes, the CTSI based

intelligent cooling strategy better aligns with human thermoregulatory and adaptive rhythms, dynamically modulates thermal load within acceptable limits, and avoids prolonged periods of overheating or over-cooling. This approach enhances comfort, reduces physiological burden, and optimizes energy efficiency.

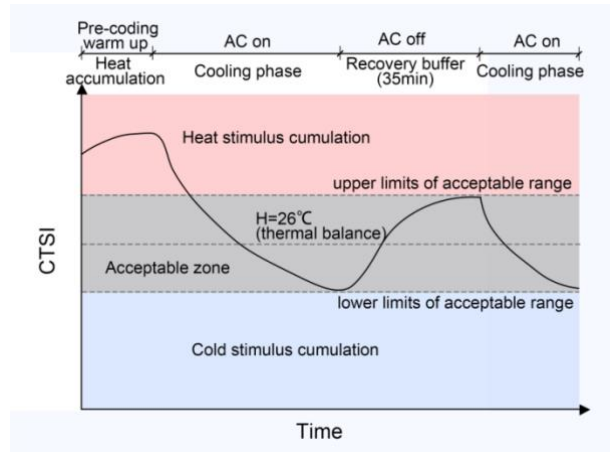


Fig. 6. CTSI based Intelligent Cooling Control Strategy in intermittent cooling environments
 This diagram illustrates a three-phase cooling strategy guided by the Cumulative Thermal Stimulus Index (CTSI), which captures both temperature deviation from the neutral point (26 °C) and exposure duration. CTSI > 0 indicates heat exposure; CTSI < 0 indicates cold exposure. The gray zone denotes the acceptable adjustment range. Cooling is activated when CTSI exceeds the upper limit and reduced or paused when it falls below the lower limit. A 35-minute recovery buffer is advised after each adjustment to allow full physiological and perceptual recovery.

4.6 Research Limitations and Future Research Recommendations

This study acknowledges several limitations: participants were Chinese university students aged 19 to 23, forming a relatively homogeneous group, which may limit the generalizability of findings across different age groups, cultural backgrounds, and climatic regions. Previous research indicates that thermal comfort and human responses are influenced by age, cultural adaptation, and degree of climate exposure. Therefore, the findings primarily reflect characteristics of young, healthy adults in summer cooling environments and require validation across more diverse populations and climatic conditions.

Additionally, the observed cooling rates stem not only from experimental design but also from the cooling capacity of split-type air conditioners and the thermal performance of the test chamber's envelope (including insulation and airtightness). These factors may limit the universality of absolute values in other buildings or systems. Nevertheless, this study focuses on the relative dynamics of physiological versus perceived responses. Moreover, the proposed CTSI framework emphasizes cumulative cold exposure rather than precise cooling rates, suggesting broader applicability. Such limitations may result in experimental cooling rates differing from those in actual buildings.

5 Conclusions

This study examined human thermophysiological and perceptual responses under intermittent cooling conditions, revealing key features of non-steady-state thermal adaptation. By monitoring skin temperature, cardiovascular activity, and subjective feedback across varying cooling intensities and durations, we proposed a new conceptual framework for evaluating dynamic thermal comfort. The main conclusions are as follows:

(1) Cooling intensity, rather than cooling rate alone, is the dominant factor in determining thermal stability and human adaptation. High cooling exposure (HCE, 20 °C) led to persistent physiological and environmental instability, while moderate (MCE, 26 °C) and low (LCE, 28 °C) exposures reached steady states within 10 - 20 minutes. This finding challenges the assumption that lower set-points always enhance cooling effectiveness and highlights the potential burden of excessive cold exposure.

(2) Prolonged high-intensity cooling causes cumulative physiological stress beyond skin-level compensation. After 20 minutes, cardiovascular indicators (e.g., elevated diastolic blood pressure and suppressed heart rate) became dominant, particularly under HCE conditions. This suggests that the body's regulatory capacity becomes overloaded, leading to a layered stress response and delayed recovery.

(3) A 35-minute universal recovery window was identified across all cooling conditions during the post-cooling phase. Subjective responses stabilized alongside skin temperature within this window, regardless of prior cooling intensity. However, recovery outcomes varied: HCE achieved the highest final comfort, while LCE experienced declining comfort even as the environment warmed, suggesting prior exposure intensity shapes perceptual recovery.

(4) Cooling and recovery phases show asymmetric regulatory dynamics, challenging linear comfort models. While HCE triggers early relief followed by late discomfort, MCE enables stable adaptation. This highlights the need to shift from steady-state models toward frameworks capturing time-dependent and intensity-sensitive thermal adaptation.

(5) We introduce the Cumulative Thermal Stimulus Index (CTSI), a unified metric for dynamic thermal load quantification. CTSI integrates both the magnitude and duration of thermal deviation from a neutral reference (26 °C), offering a continuous, physiologically explainable measure of cumulative heat or cold exposure. It serves as a candidate control variable for adaptive cooling systems.

(6) A CTSI based three-phase control strategy is proposed for intelligent air-conditioning systems. Cooling is initiated when CTSI exceeds the upper limit (heat buildup), reduced or

terminated when it falls below the lower limit (cold buildup), and adjusted dynamically within a regulatory zone. This approach better aligns with human thermoregulatory rhythms, supports comfort stability, and enhances energy efficiency. The 35-minutes recovery window provides a practical reference for timing and control logic.

In sum, this study underscores the importance of cumulative thermal stimuli — not just instantaneous conditions — in shaping human comfort and physiological responses in intermittent cooling scenarios. The proposed CTSI framework offers both theoretical insight and practical pathways for next-generation smart cooling strategies that balance comfort, health, and sustainability.

CRedit authorship contribution statement

Haiyan Yan: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **Yongxuan Guo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation. **Hui Zhang:** Writing – review & editing. **Stefano Schiavon:** Writing – review & editing. **Ruiji Sun:** Writing – review & editing. **Shengkai Zhao:** Writing – review & editing. **Zhen Sun:** Investigation, Data curation. **Fangning Shi:** Investigation, Data curation.

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Data availability

Data will be made available on request.

Appendix A

To determine the experimental design for assessing the intensity of cooling stimuli, we first conducted a preliminary questionnaire survey to evaluate local residents' preferences for air conditioner use during the summer. The distribution of air conditioner activation temperatures and preferred setting temperatures is shown in Fig. A.1 a. Regarding air conditioner activation temperatures; we found that the average activation temperature reported by respondents was 29.5 °C. The proportions of respondents who activated air conditioners

when indoor air temperatures were 26 - 27 °C and 27 - 28 °C were 1.8 % and 8.2 %, respectively, while 90 % of air conditioner activation temperatures were above 28 °C. When the air temperature rises to 28 - 29 °C, the proportion of residents turning on air conditioners sharply increases to 30.2 %, significantly higher than other temperature ranges. As the air temperature continues to rise, the proportion of residents turning on their air conditioners gradually decreases, with the following percentages: 29 - 30 °C (26.7 %), 30 - 31 °C (17.0 %), and 31 - 32 °C (10.0 %). However, the cumulative proportion of residents turning on their air conditioners gradually increases, with over 90 % of residents choosing to turn on their air conditioners when the air temperature exceeds 32° C.

Regarding temperature setting preferences (Fig. A.1 b), we found that 37 % of respondents prefer to set the air conditioner temperature to 26 °C, which is the most commonly used temperature. Additionally, 25 % of respondents indicated setting the temperature below 26 °C, with a small portion choosing extreme values below 22 °C. Notably, 39 % of residents selected temperatures exceeding the upper limit (26 °C) of the first-level thermal comfort range (24 - 26 °C), which is recommended by the “Code for Design of Heating, Ventilation, and Air Conditioning in Civil Buildings” (GB50736-2012)^[66].

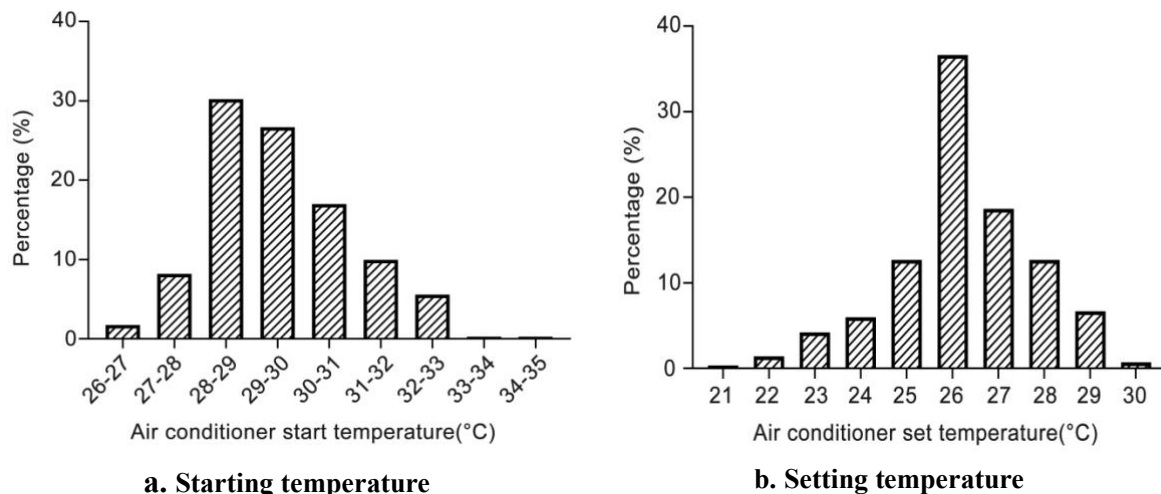


Fig. A.1 Air conditioning temperature settings in field studies

Appendix B

Table B.1 Index scales of subjective response.

Scale	Thermal sensation	Thermal acceptability	Thermal comfort
-3	Cold		Very uncomfortable
-2	Cool	Very unacceptable	Uncomfortable
-1	Slightly cool	Slightly unacceptable	Slightly uncomfortable
0	Neutral	Neutral	Neutral
+1	Slightly warm	Slightly acceptable	Slightly comfortable
+2	Warm	Very acceptable	Comfortable

Appendix C

The measurement locations are illustrated in Fig. C.1, and the mean skin temperature was calculated according to Equation (C.1).

$$MT_{sk} = 0.07T_{forehead} + 0.35T_{breast} + 0.19T_{thigh} + 0.14T_{forearm} + 0.05T_{handback} + 0.13T_{calf} + 0.07T_{ankle} \quad (C.1)$$

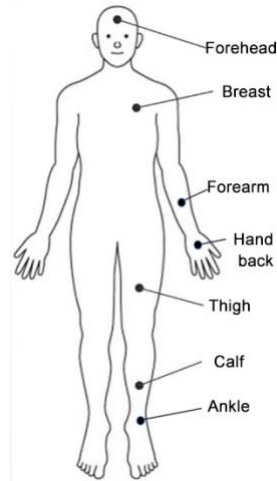


Fig. C.1 Locations of the skin temperature sensors.

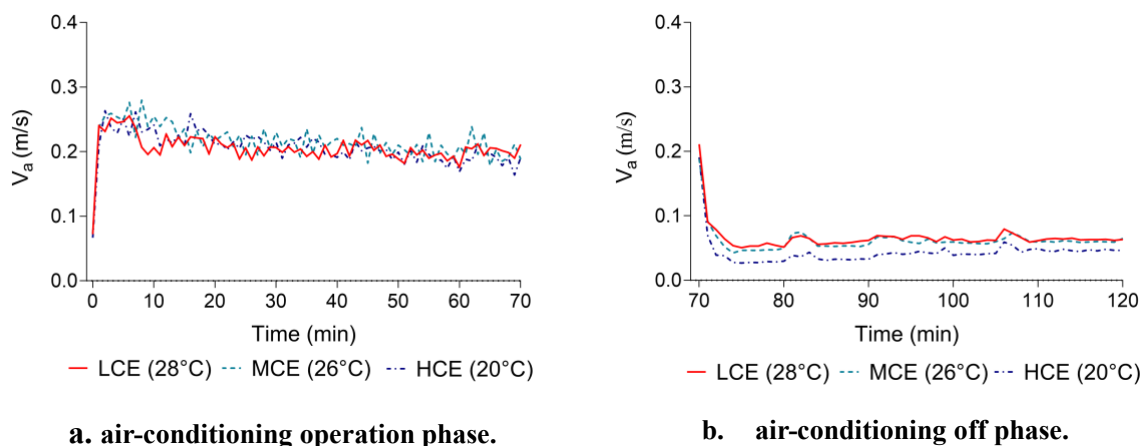
Appendix D

Figure D illustrates changes in indoor air velocity during the air conditioning operation and shutdown phases across three operating conditions. The airflow volume and supply angle remained consistent across all three experimental conditions. Statistical analysis revealed no significant differences in air velocity during the operation phase across the three conditions ($p > 0.05$), indicating that the trend of average indoor air velocity over time was largely consistent regardless of the set temperature. Within the first 5 minutes of air conditioner operation, indoor air velocity rapidly increased. After 5 minutes, the average indoor air velocity exhibited a similar rapid upward trend throughout this phase. This indicates that the air velocity environment during this stage is primarily dominated by air conditioner operation.

During the shutdown phase, with no significant indoor air source, indoor air velocity rapidly decreased immediately after shutdown across all three conditions, subsequently fluctuating between 0 - 0.1 m/s. The indoor air velocity under the high-cooling exposure condition was significantly lower ($p < .05$) than under low-cooling exposure (and moderate-cooling exposure). No significant difference existed in airflow velocity between the latter two conditions ($p > .05$). This indicates that indoor wind speeds after AC shutdown are significantly influenced by the indoor temperature state prior to shutdown. In the high-cooling-exposure (20 °C) environment, lower temperatures increase air density and weaken thermally driven

convection, resulting in significantly lower wind speeds compared to relatively warmer conditions.

To further investigate the impact of wind speed on human physiological and psychological responses, we employed Spearman correlation analysis. Results shown in Table D indicate that wind speed exhibits significant correlations with both physiological and psychological measures ($p < .01$) under low-cooling exposure conditions, with correlations stronger than those observed under medium- and high-cooling exposure conditions. Wind speed exhibited a significant positive correlation with thermal comfort in the low-cold exposure environment. This indicates that wind speed serves as a positive and effective factor for improving thermal comfort and alleviating thermal sensation in LCE conditions.



a. air-conditioning operation phase. **b. air-conditioning off phase.**
Fig. D.1 Temporal evolution of airflow velocity under three conditions (LCE: 28 °C, MCE: 26 °C, HCE: 20 °C)

Table D.1 The correlation between wind speed and reaction in three experimental scenarios

	LCE	MCE	HCE
Mean skin temperature	-0.432**	-0.474**	-0.189**
Thermal sensation	0.339**	-0.337**	-0.309**
Thermal comfort	0.338**	-0.001	-0.072
Thermal acceptability	0.331**	0.014	-0.134**

Nevertheless, given the relatively low magnitude of airflow (<0.3 m/s), airflow velocity was unlikely to be the dominant driver of the observed physiological and psychological responses compared with thermal exposure intensity.

References

- [1] Ebi K L, Capon A, Berry P, et al. Hot weather and heat extremes: health risks[J]. *The lancet*, 2021, 398(10301): 698-708. [https://doi.org/10.1016/S0140-6736\(21\)01208-3](https://doi.org/10.1016/S0140-6736(21)01208-3)
- [2] Lovcha Y, Perez-Laborda A, Sikora I. The determinants of CO2 prices in the EU emission trading system[J]. *Applied Energy*, 2022, 305: 117903.

<https://doi.org/10.1016/j.apenergy.2021.117903>

- [3] Yang L, Yan H, Lam J C. Thermal comfort and building energy consumption implications— a review[J]. *Applied energy*, 2014, 115: 164-173. <https://doi.org/10.1016/j.apenergy.2013.10.062>
- [4] Li X, Chambers J, Yilmaz S, et al. A Monte Carlo building stock model of space cooling demand in the Swiss service sector under climate change[J]. *Energy and Buildings*, 2021, 233: 110662. <https://doi.org/10.1016/j.enbuild.2020.110662>
- [5] Ruiz L G B, Pegalajar M C, Molina-Solana M, et al. A case study on understanding energy consumption through prediction and visualization (VIMOEN)[J]. *Journal of Building Engineering*, 2020, 30: 101315. <https://doi.org/10.1016/j.jobee.2020.101315>
- [6] Morris N B, Chaseling G K, English T, et al. Electric fan use for cooling during hot weather: a biophysical modelling study[J]. *The Lancet Planetary Health*, 2021, 5(6): e368-e377. [https://doi.org/10.1016/S2542-5196\(21\)00136-4](https://doi.org/10.1016/S2542-5196(21)00136-4)
- [7] De Dear R, Xiong J, Kim J, et al. A review of adaptive thermal comfort research since 1998[J]. *Energy and Buildings*, 2020, 214: 109893. <https://doi.org/10.1016/j.enbuild.2020.109893>
- [8] Liu J, Sun X, Lu B, et al. The life cycle rebound effect of air-conditioner consumption in China[J]. *Applied Energy*, 2016, 184: 1026-1032. <https://doi.org/10.1016/j.apenergy.2015.11.100>
- [9] Zhang L, Wang Y, Meng X, et al. Qualitative analysis of the cooling load in the typical room under continuous and intermittent runnings of air-conditioning[J]. *Procedia Engineering*, 2017, 205: 405-409. <https://doi.org/10.1016/j.proeng.2017.10.390>
- [10] Schellen L, van Marken Lichtenbelt W D, Loomans M G L C, et al. Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady - state condition[J]. *Indoor air*, 2010, 20(4): 273-283. <https://doi.org/10.1111/j.1600-0668.2010.00657.x>
- [11] Wu Q, Liu J, Zhang L, et al. Study on thermal sensation and thermal comfort in environment with moderate temperature ramps[J]. *Building and Environment*, 2020, 171: 106640. <https://doi.org/10.1016/j.buildenv.2019.106640>
- [12] Zhang F, De Dear R, Candido C. Thermal comfort during temperature cycles induced by direct load control strategies of peak electricity demand management[J]. *Building and Environment*, 2016, 103: 9-20. <https://doi.org/10.1016/j.buildenv.2016.03.020>
- [13] Gagge A P, Stolwijk J A J, Hardy J D. Comfort and thermal sensations and associated

- physiological responses at various ambient temperatures[J]. *Environmental research*, 1967, 1(1): 1-20. [https://doi.org/10.1016/0013-9351\(67\)90002-3](https://doi.org/10.1016/0013-9351(67)90002-3)
- [14]Chen C P, Hwang R L, Chang S Y, et al. Effects of temperature steps on human skin physiology and thermal sensation response[J]. *Building and Environment*, 2011, 46(11): 2387-2397. <https://doi.org/10.1016/j.buildenv.2011.05.021>
- [15]Xiong J, Lian Z, Zhou X, et al. Effects of temperature steps on human health and thermal comfort[J]. *Building and Environment*, 2015, 94: 144-154. <https://doi.org/10.1016/j.buildenv.2015.07.032>
- [16]Liu H, He M, Wu Y, et al. Dual effect of activity levels and temperature step-change on human comfort and recovery time: Simulated short-term commute in winter[J]. *Building and Environment*, 2024, 247: 111034. <https://doi.org/10.1016/j.buildenv.2023.111034>
- [17]Zhou F, Wang Z, Yang Y, et al. Field study on effect of large temperature steps on thermal comfort and physiological response in severe cold climate[J]. *Building and Environment*, 2025, 268: 112338. <https://doi.org/10.1016/j.buildenv.2024.112338>
- [18]De Dear R J, Ring J W, Fanger P O. Thermal sensations resulting from sudden ambient temperature changes[J]. *Indoor air*, 1993, 3(3): 181-192. <https://doi.org/10.1111/j.1600-0668.1993.t01-1-00004.x>
- [19]Liu H, Liao J, Yang D, et al. The response of human thermal perception and skin temperature to step-change transient thermal environments[J]. *Building and environment*, 2014, 73: 232-238. <https://doi.org/10.1016/j.buildenv.2013.12.007>
- [20]Höppe P. Different aspects of assessing indoor and outdoor thermal comfort[J]. *Energy and buildings*, 2002, 34(6): 661-665. [https://doi.org/10.1016/S0378-7788\(02\)00017-8](https://doi.org/10.1016/S0378-7788(02)00017-8)
- [21]Zhang X, Hu S, Liu R, et al. Study on the relationship between thermal comfort and S-IgE based on short-term exposure to temperature[J]. *Building and Environment*, 2022, 216: 108983. <https://doi.org/10.1016/j.buildenv.2022.108983>
- [22]Song C, Huang L, Liu Y, et al. Effects of indoor thermal exposure on human dynamic thermal adaptation process[J]. *Building and Environment*, 2020, 179: 106990. <https://doi.org/10.1016/j.buildenv.2020.106990>
- [23]Yu J, Ouyang Q, Zhu Y, et al. A comparison of the thermal adaptability of people accustomed to air-conditioned environments and naturally ventilated environments[J]. *Indoor air*, 2012, 22(2): 110-118. <https://doi.org/10.1111/j.1600-0668.2011.00746.x>
- [24]Ning H, Wang Z, Ji Y. Thermal history and adaptation: Does a long-term indoor thermal exposure impact human thermal adaptability?[J]. *Applied Energy*, 2016, 183: 22-30.

- <https://doi.org/10.1016/j.apenergy.2016.08.157>
- [25] Sadeghi M, de Dear R, Morgan G, et al. Development of a heat stress exposure metric—Impact of intensity and duration of exposure to heat on physiological thermal regulation[J]. *Building and Environment*, 2021, 200: 107947. <https://doi.org/10.1016/j.buildenv.2021.107947>
- [26] Gavhed D C E, Holmér I. Thermal responses at three low ambient temperatures: Validation of the duration limited exposure index[J]. *International journal of industrial ergonomics*, 1998, 21(6): 465-474. [https://doi.org/10.1016/S0169-8141\(97\)00002-4](https://doi.org/10.1016/S0169-8141(97)00002-4)
- [27] Liu W, Zhong W, Wargoeki P. Performance, acute health symptoms and physiological responses during exposure to high air temperature and carbon dioxide concentration[J]. *Building and Environment*, 2017, 114: 96-105. <https://doi.org/10.1016/j.buildenv.2016.12.020>
- [28] Kobas B, Koth S C, Nkurikiyeyezu K, et al. Effect of exposure time on thermal behaviour: a psychophysiological approach[J]. *Signals*, 2021, 2(4): 863-885. <https://doi.org/10.3390/signals2040050>
- [29] Ning H, Wang Z, Ji Y. Thermal history and adaptation: Does a long-term indoor thermal exposure impact human thermal adaptability?[J]. *Applied Energy*, 2016, 183: 22-30. <https://doi.org/10.1016/j.apenergy.2016.08.157>
- [30] Krüger E L, Tamura C A, Bröde P, et al. Short-and long-term acclimatization in outdoor spaces: Exposure time, seasonal and heatwave adaptation effects[J]. *Building and Environment*, 2017, 116: 17-29. <https://doi.org/10.1016/j.buildenv.2017.02.001>
- [31] Jia X, Li S, Zhu Y, et al. Transient thermal comfort and physiological responses following a step change in activity status under summer indoor environments[J]. *Energy and Buildings*, 2023, 285: 112918. <https://doi.org/10.1016/j.enbuild.2023.112918>
- [32] Yan H, Pan Y, Dong M, et al. Energy efficiency and comfort: analysis of thermal responses and behaviors of residents with high and low air conditioning dependency[J]. *Energy and Buildings*, 2025, 338: 115695. <https://doi.org/10.1016/j.enbuild.2025.115695>
- [33] Dai L, Li Z, Chen X, et al. Usage behavior characteristics of household air-conditioners during the extremely hot summer—A case study of Chongqing[J]. *Building and Environment*, 2023, 234: 110160. <https://doi.org/10.1016/j.buildenv.2023.110160>
- [34] Fu J, Hu S, He X, et al. Identifying residential building occupancy profiles with demographic characteristics: using a national time use survey data[J]. *Energy and Buildings*, 2022, 277: 112560. <https://doi.org/10.1016/j.enbuild.2022.112560>

- [35] Kim J, Tartarini F, Parkinson T, et al. Thermal comfort in a mixed-mode building: Are occupants more adaptive?[J]. *Energy and Buildings*, 2019, 203: 109436. <https://doi.org/10.1016/j.enbuild.2019.109436>
- [36] Jia X, Cao B, Zhu Y, et al. Thermal comfort in mixed-mode buildings: A field study in Tianjin, China[J]. *Building and Environment*, 2020, 185: 107244. <https://doi.org/10.1016/j.buildenv.2020.107244>
- [37] Jiang Y, Xie Y, Niu J. Short-term dynamic thermal perception and physiological response to step changes between real-life indoor and outdoor environments[J]. *Building and Environment*, 2024, 251: 111223. <https://doi.org/10.1016/j.buildenv.2024.111223>
- [38] Jia X, Li S, Zhu Y, et al. Transient thermal comfort and physiological responses following a step change in activity status under summer indoor environments[J]. *Energy and Buildings*, 2023, 285: 112918. <https://doi.org/10.1016/j.enbuild.2023.112918>
- [39] Yang Y, Wang Z, Su X, et al. Thermal responses and skin temperature to moderate temperature ramps in winter: an office-lab study[J]. *Building and Environment*, 2022, 225: 109682. <https://doi.org/10.1016/j.buildenv.2022.109682>
- [40] Al-Mumin A, Khattab O, Sridhar G. Occupants' behavior and activity patterns influencing the energy consumption in the Kuwaiti residences[J]. *Energy and buildings*, 2003, 35(6): 549-559. [https://doi.org/10.1016/S0378-7788\(02\)00167-6](https://doi.org/10.1016/S0378-7788(02)00167-6)
- [41] D'oca S, Fabi V, Corgnati S P, et al. Effect of thermostat and window opening occupant behavior models on energy use in homes[C]//*Building Simulation*. Springer Berlin Heidelberg, 2014, 7: 683-694. <https://doi.org/10.1007/S12273-014-0191-6>
- [42] ISO I S O. 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria[J]. *Management*, 2005, 3(605): e615.
- [43] Li J, Deng W, Yan G. Improving quick cooling performance of a R410A split air conditioner during startup by actively controlling refrigerant mass migration[J]. *Applied Thermal Engineering*, 2018, 128: 141-150. <https://doi.org/10.1016/j.applthermaleng.2017.08.151>
- [44] Nagano K, Takaki A, Hirakawa M, et al. Effects of ambient temperature steps on thermal comfort requirements[J]. *International journal of biometeorology*, 2005, 50: 33-39. <https://doi.org/10.1007/s00484-005-0265-3>
- [45] Huang S, Katipamula S, Lutes R. Experimental investigation on thermal inertia characterization of commercial buildings for demand response[J]. *Energy and Buildings*, 2021, 252: 111384. <https://doi.org/10.1016/j.enbuild.2021.111384>

- [46] Xiong J, Zhou X, Lian Z, et al. Thermal perception and skin temperature in different transient thermal environments in summer[J]. *Energy and buildings*, 2016, 128: 155-163. <https://doi.org/10.1016/j.enbuild.2016.06.085>
- [47] Wu Q, Liu J, Zhang L, et al. Study on thermal sensation and thermal comfort in environment with moderate temperature ramps[J]. *Building and Environment*, 2020, 171: 106640. <https://doi.org/10.1016/j.buildenv.2019.106640>
- [48] Ergonomics of the thermal environment-Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria[M]. ISO, 2005.
- [49] Fanger P O. Thermal comfort. Analysis and applications in environmental engineering[J]. <https://doi.org/1970.10.5555/19722700268>
- [50] Liu J, Kang J, Li Z, et al. Overall effects of temperature steps in hot summer on students' subjective perception, physiological response and learning performance[J]. *Energy and Buildings*, 2021, 247: 111124. <https://doi.org/10.1016/j.enbuild.2021.111124>
- [51] Ivanova Y M, Pallubinsky H, Kramer R, et al. The influence of a moderate temperature drift on thermal physiology and perception[J]. *Physiology & behavior*, 2021, 229: 113257. <https://doi.org/10.1016/j.physbeh.2020.113257>
- [52] Ji W, Cao B, Geng Y, et al. Study on human skin temperature and thermal evaluation in step change conditions: From non-neutrality to neutrality[J]. *Energy and Buildings*, 2017, 156: 29-39. <https://doi.org/10.1016/j.enbuild.2017.09.037>
- [53] Luo W, Kramer R, de Kort Y, et al. The effects of a novel personal comfort system on thermal comfort, physiology and perceived indoor environmental quality, and its health implications-Stimulating human thermoregulation without compromising thermal comfort[J]. *Indoor Air*, 2022, 32(1): e12951. <https://doi.org/10.1111/ina.12951>
- [54] Jiang A, Cheng Y, Wu Y, et al. Effect of temperature step-changes and ramps on physiological and psychological responses of occupants in office buildings in summer[J]. *Building and Environment*, 2024, 259: 111631. <https://doi.org/10.1016/j.buildenv.2024.111631>
- [55] Bai Y, Zhang Y, Wei Z, et al. Experimental study on human comfort responses after simulated summer commutes with double transients of temperature and metabolic rate[J]. *Building and Environment*, 2022, 221: 109253. <https://doi.org/10.1016/j.buildenv.2022.109253>
- [56] Tartarini F, Schiavon S, Cheung T, et al. CBE Thermal Comfort Tool: Online tool for thermal comfort calculations and visualizations[J]. *SoftwareX*, 2020, 12: 100563.

<https://doi.org/10.1016/j.softx.2020.100563>

- [57] Gilani S I H, Khan M H, Ali M. Revisiting Fanger' s thermal comfort model using mean blood pressure as a bio-marker: An experimental investigation[J]. *Applied thermal engineering*, 2016, 109: 35-43. <https://doi.org/10.1016/j.applthermaleng.2016.08.050>
- [58] Li Y, Geng S, Zhang X, et al. Study of thermal comfort in underground construction based on field measurements and questionnaires in China[J]. *Building and Environment*, 2017, 116: 45-54. <https://doi.org/10.1016/j.buildenv.2017.02.003>
- [59] Brager G S, De Dear R J. Thermal adaptation in the built environment: a literature review[J]. *Energy and buildings*, 1998, 27(1): 83-96. [https://doi.org/10.1016/S0378-7788\(97\)00053-4](https://doi.org/10.1016/S0378-7788(97)00053-4)
- [60] Maiti R. PMV model is insufficient to capture subjective thermal response from Indians[J]. *International Journal of Industrial Ergonomics*, 2014, 44(3): 349-361. <https://doi.org/10.1016/j.ergon.2014.01.005>
- [61] Harris A M, MacBride L R, Foster R C, et al. Does non-exercise activity thermogenesis contribute to non-shivering thermogenesis?[J]. *Journal of Thermal Biology*, 2006, 31(8): 634-638. <https://doi.org/10.1016/j.jtherbio.2006.08.007>
- [62] Ghahramani A, Tang C, Yang Z, et al. A study of time-dependent variations in personal thermal comfort via a dynamic bayesian network[M]//*Sustainable human - building ecosystems*. 2015: 99-107
- [63] Zhang Y, Zhao R. Relationship between thermal sensation and comfort in non-uniform and dynamic environments[J]. *Building and Environment*, 2009, 44(7): 1386-1391.
- [64] Vellei M, Pigliautile I, Pisello A L. Effect of time-of-day on human dynamic thermal perception[J]. *Scientific Reports*, 2023, 13(1): 2367.
- [65] Wu Y, Zhang Z, Liu H, et al. Age differences in thermal comfort and physiological responses in thermal environments with temperature ramp[J]. *Building and Environment*, 2023, 228: 109887.
- [66] Xu W, Zou Y, Xu H, et al. Design Code for Heating, Ventilation, and Air Conditioning in Civil Buildings GB50736-2012 [J]. *Construction Science and Technology (Ministry of Housing and Urban-Rural Development)*, 2015, 10.