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Psychophysical Adaptations to Pre-cooling in Transient Thermal Environments

Nur Dalilah Dahlan[a]

[a] Department of Architecture, Faculty of Design and Architecture, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.

**Corresponding author: nurdalilah@upm.edu.my*

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ABSTRACT

The application of the thermal alliesthesial concept through pre-cooling strategies in tropical buildings has attracted customers by purging surplus body heat, particularly at the entry point of their transitional space. However, there is little empirical evidence on the impact of thermal alliesthesia on the human subject's perception of sensation and pleasantness. This study aims to investigate this relationship in the thermoneutral zone and various affective responses based on simulated transient thermal environments. Twenty nine healthy college-aged participants are recruited for a series of thermal alliesthesia climate chamber experiments. The predominant ET setting refers to the participant's preferred temperature, that is, 25.1 °C (±1.0). Three experiment stages with a total of nine hours, namely, Stage A (predominant ET*: 22 °C), Stage B (predominant ET*: 24 °C), and Stage C (predominant ET*: 26 °C) are devised to simulate the working commute of office workers in and out of an air-conditioning building during warm weather conditions. The results show that a high proportion of participants are indifferent up to 11 °C of down-step despite encountering corrective transitions within the thermoneutral zone. Pre-cooling strategies are not successful in eliciting thermal pleasure responses in any of the three stages. These findings suggest that a preconditioned indoor environment of 24 to 26 °C ET* is thermally sufficient when designing for transient thermal environments, thereby, eliminating the need for over-cooling.*

Keywords: Thermal alliesthesia; thermal sensation vote; thermal shock; transient thermal environment; psychophysical measurement; climate chamber experiment

INTRODUCTION

The usage of air-conditioning in built environments has been revised, particularly in countries where it is deemed unnecessary. Numerous works that propose a sustainable energy policy suggest less reliance on air-conditioning in transitional spaces such as shopping malls, hotels, offices, and even homes (Healy 2008; Hitchings & Shu Jun Lee 2008; Shove, Walker & Brown 2013). In this context of adoption of pre-cooling control strategies, there are some obvious cost-effective and energy-reduction strategies that maintain the desired thermal comfort (Wang, Tang & Song 2020).

Pre-cooling tests yielded 30% energy savings compared to existing building control (Platt, Ward & Wall 2011). Furthermore, higher space temperatures of approximately 26 °C with relative humidity levels of approximately 60% have been shown to be acceptable with respect to thermal comfort in the tropics. The potential reduction in cooling loads and energy savings resulting from a high space temperature of 26.8 °C has been illustrated in some studies (Sekhar 1995). Results from a field survey indicate that approximately 79% participants find that the enclosed lift lobby can run at higher temperature settings rather than the common practice of 16–20 °C (Kwong & Adam 2011). (Yamtraipat et al. 2006) reported that in Thailand, the most suitable proposed temperature in office buildings is 26 °C with a preferred relative humidity range of 50%–60% RH.

An understanding of occupants' perceptual responses to transient thermal environments is important for the design of sustainable and energy-efficient buildings. Pioneers of psychophysical investigations of thermal environments have noted the importance of positive thermal alliesthesia as an alternative means (beyond conventional air-conditioning) of heat transfer within the boundary layer between the building occupants and indoor environment (M. Attia & Engel 1981; Cabanac 1971; Richard. de Dear 2011). Thermal alliesthesia describes the circumstances in which a given stimulus can induce either pleasant, unpleasant, or indifferent sensations (affective dimensions) depending on the subject's body temperature regulation. Pleasure is perceived as useful, healthy, and delightful; thus, it becomes a decision-making mechanism for the subject when confronted with transient thermal environments with large temperature differences (Cabanac 1992; Heschong 1978). However, psychophysical investigations of comfort in indoor transient environments, which include the occupants' empirical thermal pleasure responses, are still lacking (Makoto 2009; Parkinson, de Dear & Candido 2012; Takada, Matsumoto, & Matsushita, 2013; Zhang et al. 2010a, 2010b, 2010c; Zhang et al. 2010).

Regardless of the pre-cooling strategies, used to elicit cool pleasantness, adopted in actual tropical buildings, this study assumes that a high proportion of occupants will express thermal pleasure once they encounter down-step changes. Conversely, if thermal perception assessments modulate these effects, the response would worsen under a less preferred temperature because of the larger temperature difference. Here, the effects of pre-cooling on building occupants through their thermal psychophysical responses are investigated against three different effective temperatures. These temperatures are slightly higher than the ambient temperature typically maintained in offices. This study aims to deduce the relationship between thermoregulatory effects and various affective responses based on the transient thermal environment. The experiments are designed to simulate three thermoneutral zones based on the temperature preferences of the samples. Corrective potentials from peripheral heat transfer due to presence of pre-cooling exposure, or vice versa, are observed. A series of experiments are conducted in the Indoor Environmental Quality (IEQ) lab, Australia (Richard de Dear et al. 2013) utilising three conjoining walk-in climate chambers.

METHODOLOGY

THERMAL ALLIESTHESIA EXPERIMENT

Thermal alliesthesia is investigated to describe the association of thermal sensation (i.e., affective dimension) with behaviour. According to Cabanac (Cabanac 1971, 1992), a given stimulus may elicit either pleasure or displeasure based on the thermoregulatory state of the participant. The short-term application of thermal alliesthesia, that is through transient thermal environments (Cabanac 1971; Elnabawi & Hamza 2020), is used. The thermal sensation vote (TSV) and thermal pleasure vote (ΨPles) belong to two different dimensions of the physiological and the psychological, respectively. This study uses 'Ψ' as the symbol for thermal alliesthesia to signify its origin in the psychology literature (Cabanac et al. 2002).

The participants' preferred temperature in the experiments is determined as the thermoregulatory set point based on the method used by (Cabanac et al. 1971). An increase in thermal alliesthesia is due to falling core and mean skin temperatures, such that if both core and mean skin temperatures diverge, the signal from the core overrides the signal from the skin (Moneim Attia 1984). The sign and size of the load error (Figure 1) between the thermoregulatory set point and the prevailing body temperature determines the direction and extent of the behavioural and autonomic thermoregulatory defence mechanisms. These mechanisms will then act to reduce the load error to acceptable thermal comfort limits (M. Attia, Engel & Hildebrandt 1980; Benzinger 1969; Romanovsky 2014).

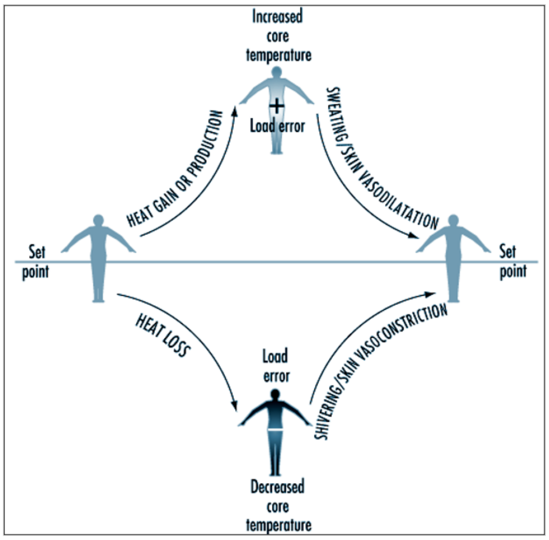

FIGURE 1. Model of thermoregulation in the human body
Source: Encyclopaedia of Occupational Health and Safety (CISILO, 2013)

The mean preferred temperature of 25 °C (±1.0) is collected for the study sample. The experiment details can be obtained in (Dahlan 2017). The preferred temperature, also known as the most pleasant temperature, is inversely proportional to body temperature (Tb) (Cabanac et al. 1971) (Equation 1). A certain temperature stimulus may elicit a pleasant or unpleasant response based on how well it can restore the internal body temperature to its thermoregulatory set point (Cabanac 1971).

$$T_b = (T_c \times 0.7) + (T_{sk} \times 0.3) \quad (1)$$

where T_c is the core temperature and Tsk is the skin temperature.

However, studies have shown that Tc has a much lower influence on human affective votes than Tsk. This is because the range of variation in Tc is, in general, significantly smaller than Tsk (Hardy & Stolwijk 1966; Takada et al. 2013). In this study, the skin temperatures are measured based on Hardy and DuBois' 7-point method (Mitchell & Wyndham 1969) (Equation 2):

$$T_{sk} = 0.07 \times T_{sk,\,head} + 0.14 \times T_{sk,\,forearm} + 0.05 \times T_{sk,\,hand} + 0.35 \times T_{sk,\,abdomen} + 0.19 \times T_{sk,\,thigh} + 0.13 \times T_{sk,\,legs} + 0.07 \times T_{sk,\,instep} \quad (2)$$

ΨPles and TSV are investigated under transient states. This study adopts the formula for change of ΨPles (Δ ΨPles) and TSV (ΔTSV), respectively, as follows:

where t_1 and t_{-1} are the readings taken one minute after and before a transition, respectively. Equations 3 and 4 continue until the final minute of Chamber 2 bouts.

Under transient environments, the differences in occupants' thermal sensation become more pronounced because of the more rapid adjustment of changes in skin temperature (Auliciems 1981; Liao 1977). Exposure to any environment that tends to normalise the mean body temperature is perceived as comfortable (1981). Recent investigations have examined the effects of both transient temperatures and metabolic rate (Goto et al. 2006; Kenny, Jay & Journeay 2007; Ugursal & Culp 2012). These studies suggest that the psychophysical rating for tolerance of transient thermal sensations will last for up to approximately 10 min before reaching a neutral state. For example, (Goto et al. 2006) investigated the effect on thermal perception and thermo-physiological variables of controlled metabolic excursions of various intensities and durations. The authors suggest that after approximately 15–20 minutes under constant activity, the subject's thermal response approached the steady-state response. In another more intense experiment, despite a moderate operative temperature ramp exposure, it was found that sick building syndrome symptoms, such as headache, lesser concentration ability, and general well-being, significantly affected sedentary subjects when exposure times exceeded 4 h (Kolarik et al. 2009). This study considers a shorter duration to thermoneutral exposure of 70 min, which includes 50 min of steady-state response.

PARTICIPANTS

A total of 29 students were recruited as participants from the University of Sydney, Australia, including 12 males and 17 females. Twelve participants were South Americans, eight were Chinese, three were Anglo Saxons, two were Indians, two were Middle Easterners, and two were Europeans. Participants were instructed to wear standard uniforms, which included a long-sleeved cotton twill shirt, denim long trousers, socks, covered shoes, and their own underwear (bra and briefs for females, briefs for males). The clothing insulation value of this light summer ensemble was 0.60 clo, following (Rohles 1973). The study was approved by the Human Research Ethics Committee (HREC) at the University of Sydney (protocol number 14285). All participants provided written informed consent and were reimbursed for participation according to the established allowances.

a) CorTemp® Sensor b) CorTemp® recorder c) DataTaker DT80 & Thermocouples

d) Polar H1 heart rate monitor

FIGURE 2. Instruments used in the experiment

INSTRUMENTS

The participants' core temperatures were detected using CorTemp® sensor pills that were ingested 8 h before the scheduled session. On the previous day, participants were reminded to ingest their CorTemp® sensor pill at approximately 11 p.m. for those attending the morning session, or at 6 a.m. on the same day for those attending the afternoon session. The sensor's signal of 262 kHz or 300 kHz passes harmlessly through the body to the CorTemp® Data Recorder worn outside the body (Figures 2a and 2b). The sensor passes through the body at the subject's normal rate of motility, which can vary anywhere from 24 to 36 hours. The CorTemp® sensor is accurate to ± 0.1 °C. It has been cleared and registered with the Food and Drug Administration (FDA) as a single use device. The CorTemp® Data Recorder also captures the participant's heart rate transmitted using a Polar H1 heart rate monitor (Figure 2d). The core temperature and heart rate were recorded every 5 min. Seven-point skin temperatures at the forehead, left dorsal hand, left forearm, left abdomen, left anterior shin, left anterior thigh, and left instep were measured using thermocouples (T-type, 0.2 mm diameter). The data were recorded using the DT80 series DataTaker datalogger manufactured by Thermo Fisher Scientific™, USA (Figure 2c). The temperature range for the thermocouple was from −59 °C to +370 °C, typically in 0.2 °C intervals with an accuracy of ±0.5 °C within 0 °C to +70 °C. The data were monitored at 30 s intervals.

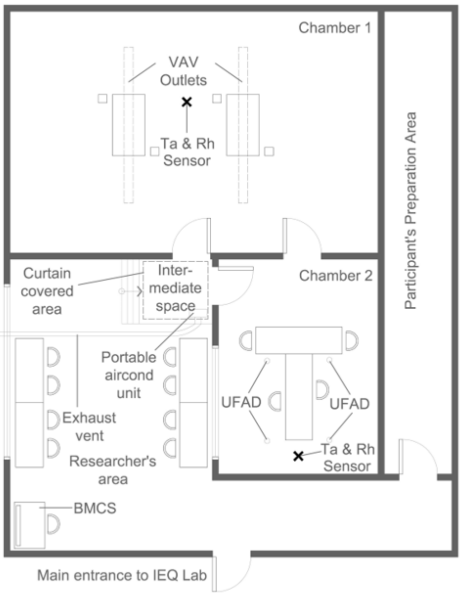

FIGURE 3. Experiment arrangement
Note:Dimensions for the chambers are as follows: Chamber 1: 8.85 m (l) × 6.85 m (w) x 2.60 m (h); Chamber 2 is 4.2 m (l) × 5.63 m (w) x 2.60 m (h); and the intermediate space: 1.5 m (l) x 1.5m (w) x 2.6 m (h).

The whole-body thermal sensation, pleasure, and acceptability psychometric scales were recorded using a self-administered wireless survey tablet when exposed to transient environments. The transient environments simulate the typical journey of an office worker who moves from a warm outdoor environment (i.e., 33 °C ET*) into an air-conditioned office with a uniform temperature set-point. The thermal perception questions were as follows:

1. How would you rate your current thermal sensation? [Scale used: -3 (cold) to +3 (warm)];
2. How would you rate your current thermal pleasure? [Scale used: -3 (strong thermal displeasure) to +3 (strong thermal pleasure)]; and
3. Do you accept this thermal environment? [Scale used: -1 (unacceptable), 0 (not sure), and +1 (acceptable)].

Questions were set to recur every five minutes. Once a vote was cast, a countdown screen appeared, indicating the remaining time to anticipate the next question. The 'back' buttons were disabled to prevent participants from changing their real-time votes.

EXPERIMENT PROCEDURE

Experiments were conducted in the Indoor Environmental Quality Lab at the University of Sydney from 28 October to 20 November 2013. The study had a repeated-measures design. Each session was three and a half hours long, including 30 min for experiment preparation. The experiment comprised three stages, A, B, and C, where the predominant new ET* programmed in Chamber 2 was 22, 24, and 26 °C, respectively. The ET* in Chamber 1 and the intermediate space remained unchanged throughout the experiment. The maximum number of participants per session was four. Two experiment sessions were performed for four days a week each: a morning session (9 a.m. until 12:30 p.m.) and an afternoon session (1 p.m. until 4:30 p.m.). By using the online meeting schedule tool, Doodle, participants chose the date and time (i.e., either to attend the morning or afternoon session) suitable for them. The follow-up experiment session for each participant comes after a seven-day gap. Figure 4 illustrates the thermal alliesthesia experiment procedure with the five step-changes labelled from 'a' to 'e', respectively.

Within 30 min of their arrival in the lab, each participant was instructed to fasten the thermocouple wires at seven skin points and then to put on the clothing ensemble provided. Participants were first exposed to ET* of 33 °C in Chamber 1 for 15 min while performing a simple stepping routine (Figure 5). Next, participants were instructed to enter Chamber 2, and once seated, were asked immediately to rate their thermal perceptions. Then, they

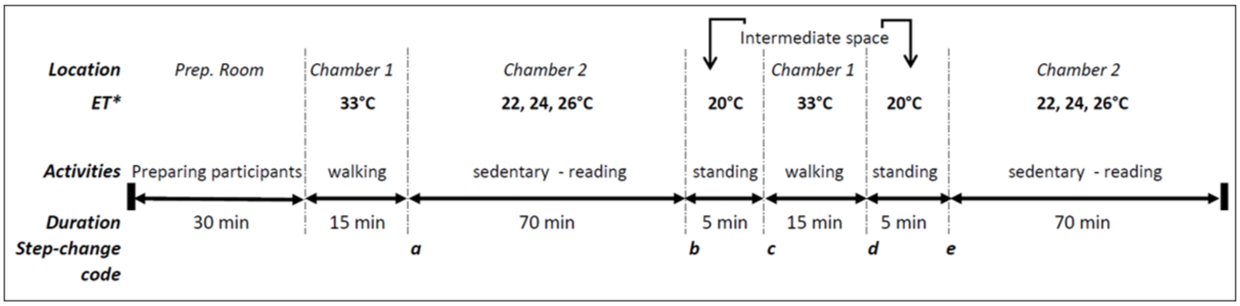

FIGURE 4. Flow chart of procedure for the Thermal Alliesthesia experiment. New effective temperature (ET*) is the temperature of a standard environment: mean radiant temperature (MRT) = Air temperature; (RH) = 50 %; wind speed < 0.15 ms-1. Metabolic rate is limited to low activity and light clothing. (Total experiment duration: 180 + 30 min for preparation).

FIGURE 5. Participant performing a stepping routine in Chamber 1

FIGURE 6. Participants performing sedentary tasks in Chamber 2

FIGURE 7. Intermediate space

were given leeway to perform simple sedentary tasks for 70 min (Figure 6). They were later asked to enter the intermediate space and immediately rate their thermal perceptions while standing for 5 min (Figure 7).

Step-change experiments were grouped based on ΔT. The direction of the thermal load error is shown in Figure 8. Below 20 °C and above 33 °C were considered as cold and warm discomfort regions, respectively. The individual

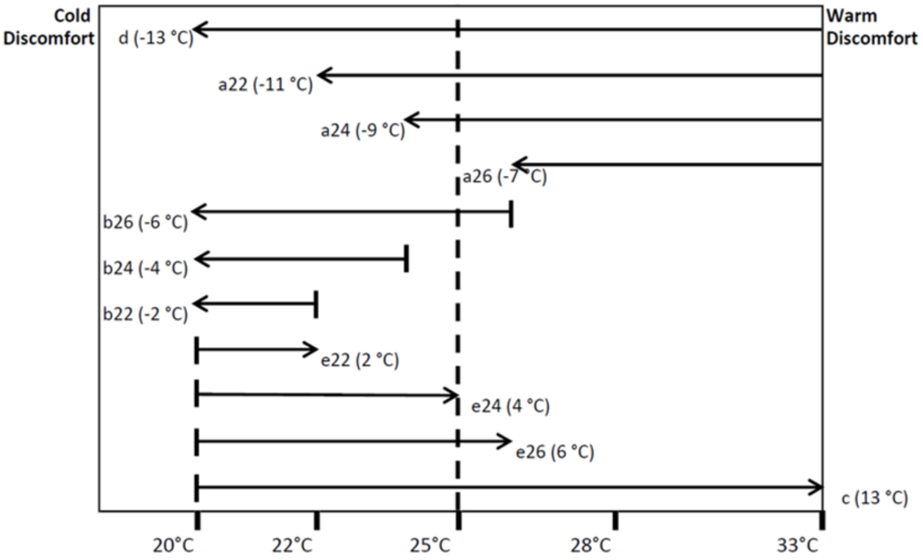

FIGURE 8. Step-change experiments based on temperature difference (in parentheses) and load error directions (arrows). 25 °C is the mean preferred temperature for this sample. Left arrow shows negative load error, and vice-versa.

step-change experiments depicted in Figure 8 were arranged to facilitate comparison among the down-steps and their up-step counterparts. To investigate the effects of pre-cooling on building occupants, the responses detected in step-changes a22, a24, and a26 that represent the load error direction for non-pre-cooling conditions were compared against their counterparts in step-changes e22, e24, and e26.

DATA ANALYSIS

Descriptive analyses were used to obtain insights into anthropometric characteristics, skin and core temperatures, and thermal perception votes. Paired-sample t-tests were used to compare the mean differences in TSV and ΨPles between the with and without pre-cooling conditions. A one-way ANOVA test was used to determine the mean differences in the TSV and ΨPles among participants at the three experiment stages. Statistical tests were conducted at a 5% significance level ($p < 0.05$). All data were analysed using the statistical software IBM SPSS Statistics v.20.

RESULTS AND DISCUSSION

THERMOREGULATORY EFFECTS ON TRANSIENT THERMAL ENVIRONMENTS

The participants underwent a total of nine hours experiment sessions that were divided equally into Stages A, B, and C. Almost all of the participants came to their scheduled experiment sessions except for two absentees. One participant was absent for Stage A because of a last-minute work obligation and another missed the Stage C experiment due to a health issue. The total experimental time was 4 320 min throughout a series of 24 experiments. The time interval for recording the thermal perception votes, heart rate and Tc was 5 min; thus, 3 132 datasets should be obtained with 36 votes per session. The total available dataset for Tsk is 30 600, which was collected every 30 s. It should be noted that the lost dataset only accounts for 2%, thus is deemed sufficient for data analysis.

The participants' anthropometric information is shown in Table 1. Figure 9 shows the participants' mean skin temperatures, local hand skin temperatures, core temperatures, and heart rates in all three stages. There are three shades shown in Figures 9a, 9b, and 9c that distinguish the temperature, activity, and location of the experiment. The dark grey zone represents 33 °C ET*, while performing a mild step routine in Chamber 1. The light grey zone represents 20 °C ET* while standing at ease in the intermediate space. The white zones in Figures 9a, 9b, and 9c represent 22 °C ET*, 24 °C ET*, and 26 °C ET*, respectively, in Chamber 2. In this chamber, participants were instructed to perform sedentary tasks.

TABLE 1. Participant anthropometric information

		Mean		
Gender	n	Age	Weight (kg)	Height (cm)
Male	12	31.5, ±4.7	83.1, ±10.2	177.2, ±8.1
Female	17	28.2, ±3.3	56.2, ±7.3	162.1, ±6.3

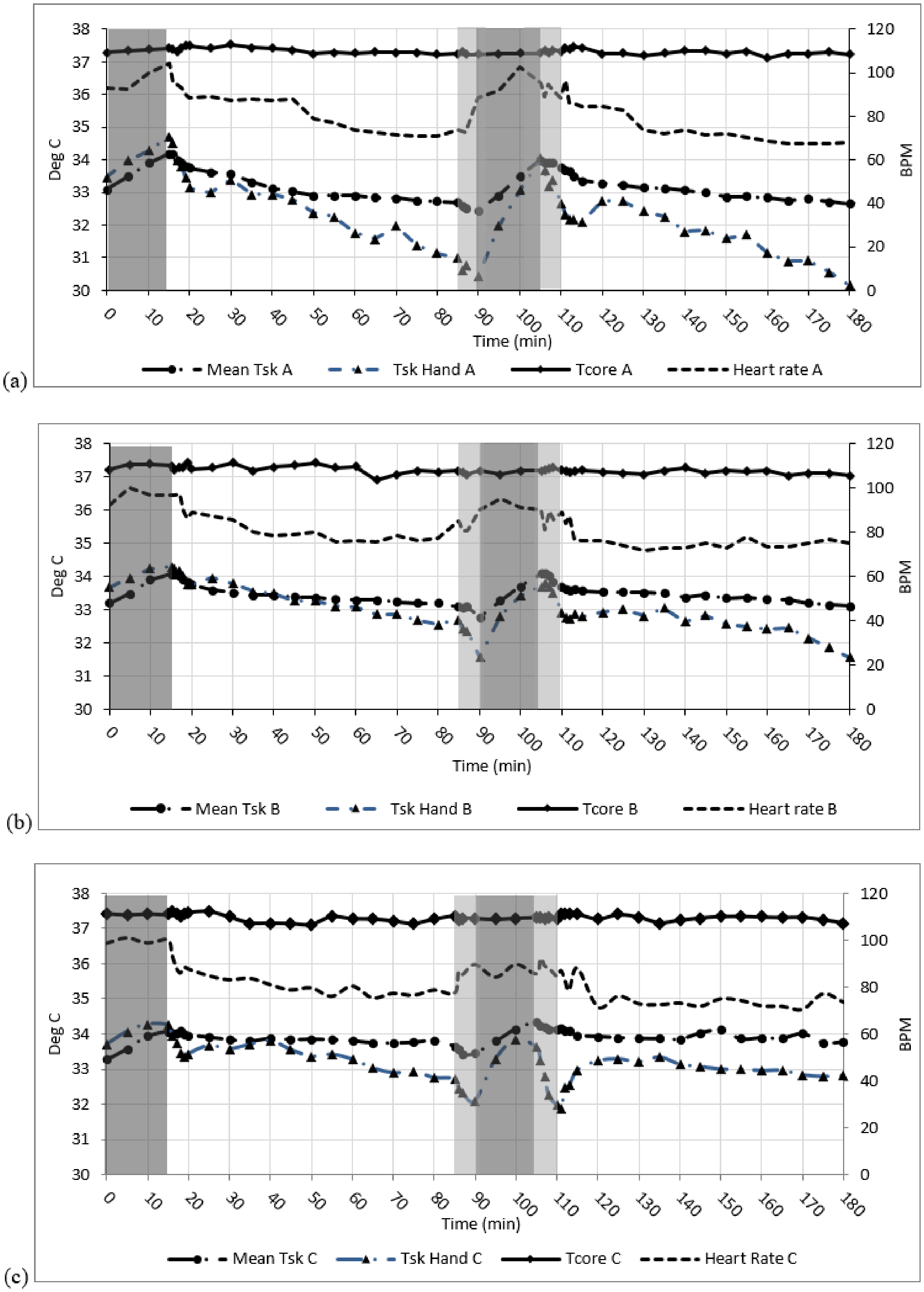

FIGURE 9. (a) Participants' measurements in Stage A; (b) Participants' measurements in Stage B; (c) Participants' measurements in Stage C. Dark grey zone: ET* = 33 °C, step routine. Light grey zone: ET* = 20 °C, standing at ease. Step-changes are indicated at 'a' (t_{15}), 'b' (t_{85}), 'c' (t_{90}), d (t_{105}), and e (t_{110}).

Substantial changes in the heart rates and skin temperatures were observed in response to temperature and metabolic changes. Normal heart rates ranging from 65 to 95 beats per minute (bpm) were detected throughout the experiments. The plateaued heart rate, depicting the steady state condition in Chamber 2, is usually associated with loss of focus and sleepiness, while shivering was observed more frequently approximately 30 min after step-changes at a22 and e22. Skin temperature detected at the dorsal hand (Tsk Hand), as an extremity, was more sensitive to changes in ET* compared to the mean skin temperature (Mean Tsk).

Changes in the participants' thermal pleasure votes (ΔΨPles) in 11 step-change experiments were collected to indicate thermal pleasure, indifference, or thermal displeasure votes. Figure 10 shows the percentage of thermal pleasure votes with respect to the magnitude of the temperature difference in a given step-change experiment. Large temperature difference down-step transitions that include both metabolic heat gain and temperature transients, as observed in step-changes a22, a24, a26, and d, elicited instantaneous and strong thermal pleasure responses. This corroborates with the findings from (Parkinson et al. 2012). The slightly lower percentage of thermal pleasure detected in step-changes d and a22 has two possible explanations. First, the metabolic rate change experienced by participants at the onset of step-change d occurred less drastically compared to a22, a24, and a26. This is because after performing light step exercises for 15 min (metabolic rate of 115 Wm-2), participants were required to stand at ease (metabolic rate of 70 Wm-2) for 5 min. The metabolic heat gain of some participants did not diminish entirely during this period. Second, the ambient temperature of 20 °C may have been too low for some participants and may have induced a sense of 'thermal shock'.

A less intense thermal shock was induced at the onset of step-change *a22* because of a smaller temperature difference than that observed in step-change *d* and *a* lower metabolic rate of 60 Wm-2 (performing sedentary tasks). Figure 9a shows that participants had a slightly higher heart rate compared to other *a* and *e* transitions, of approximately 85 to 90 bpm for 30 and 15 min after the *a22* and *e22* transitions, respectively. A behavioural thermoregulatory response, such as shivering, was elicited immediately at the onset of *a22*. Participants experienced extremity (hand) cooling at an ET* of 22 °C sustained for 70 min while performing a sedentary task. This is an early sign of cold stress (Figure 9a).

Thermal displeasure responses were observed in step-changes *b22, b24, b26, e22, e24, e26*, and *c* (Figure 10). The small temperature differences in these transitions were not sufficient to induce either automatic or behavioural thermoregulatory responses; instead, they caused 'thermal boredom'. A steady heart rate of approximately 70 bpm approximately 10 min after entering Chamber 2, as observed in step-changes *a24, a26, e24, and e26*, suggests that participants were relaxed, and some even started feeling sleepy (Figures 9b and 9c). The inverse correlation between the number of different thermal sensation votes and the magnitude of temperature difference beyond -2 °C (step-change b22) may validate the fact that participants experienced thermal boredom (Figure 10).

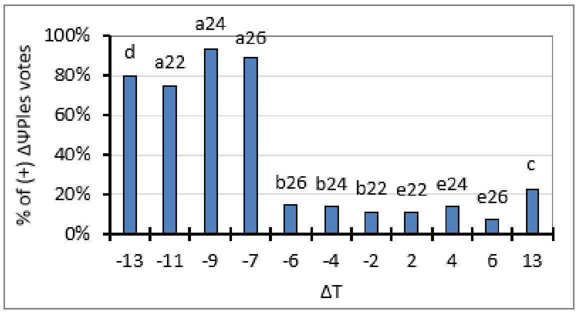

FIGURE 10. Percentage of positive ΔΨPles votes against ΔT.

It is unclear whether exposure to a lower temperature or a change in metabolic rate hindered thermal pleasure when measured at the onset of step-changes *d* and *a22*. Nevertheless, the highest percentage of thermal pleasure votes was reported at step-change *a24*, followed by *a26*, as shown in Figure 10. This may indicate that the down-step transition into a preconditioned chamber of 24 °C ET* is more effective at triggering thermal pleasure when it follows exposure to 33 °C ET* and a mild metabolic rate task of 115 Wm-2.

Participants' thermal acceptance responses for step-changes *a, b*, and *c* showed an inverse relationship with ΔT. Participants showed a high level of thermal acceptance in all three step-changes *e* (Figure 11), but with a lower positive thermal pleasure vote, as shown in Figure 10. Meanwhile, the TSV indicates an increasing percentage of indifferent thermal sensations (Figure 12). This suggests that participants thermally accepted a slightly warmer environment after exposure to a pre-cooling environment of 20 °C, as experienced in step change *c*. In contrast, a temperature difference of -13 °C may induce thermal pleasure but can be thermally less desirable after prolonged exposure to a cool temperature of 20 °C for up to 5 min.

Responses from step-changes *b, c,* and *d* are considered as filler tasks and are not addressed in the following assessments. The correlation between the mean TSV and mean ΨPles is shown in Figure 13. Notably, 90% of the thermal pleasure is inversely influenced by the thermal sensation responses throughout the entire experiment bouts.

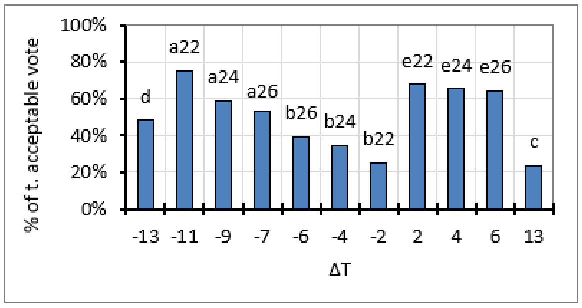

FIGURE 11. Percentage of thermal acceptable vote against ΔT.

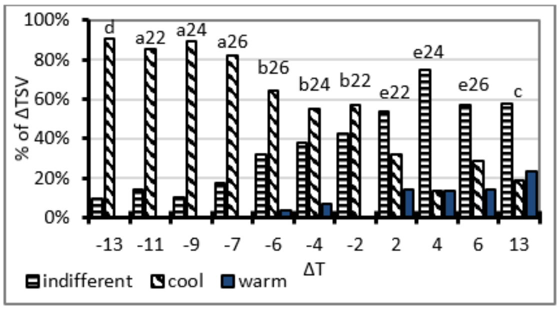

FIGURE 12. Percentage of ΔTSV against ΔT.

PRE-COOLING EFFECTS ON THERMAL SENSATION AND THERMAL PLEASURE VOTES

Responses from step-changes *b, c*, and *d* are considered as filler tasks and are not addressed in the following assessments. The correlation between the mean TSV and mean ΨPles is shown in Figure 13. Notably, 90% of the thermal pleasure is inversely influenced by the thermal sensation responses throughout the entire experiment bouts.

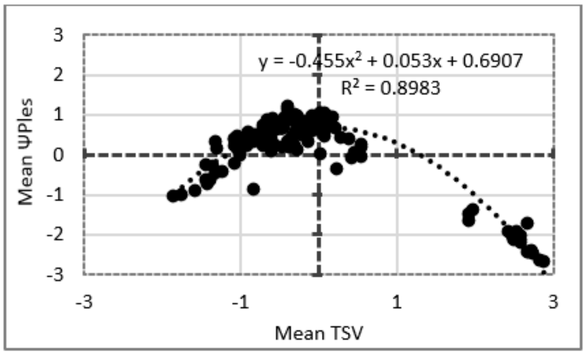

FIGURE 13. Thermal perception votes in Stages A, B, and C.

The largest temperature decreases of -1.0 °C and -1.2 °C at the onset of the steady state (at t30) in the pre-cooling and without precooling conditions, respectively, is shown in Stage A (Figure 14a). A lower skin temperature decrease was detected with an increase in down-step temperature differences (Figures 14b and 14c). The mean Tsk in Stage C shows a significant difference in means ($p < 0.01$) between the pre-cooling conditions, using one-way ANOVA. However, no significant difference in means was detected in the other two stages.

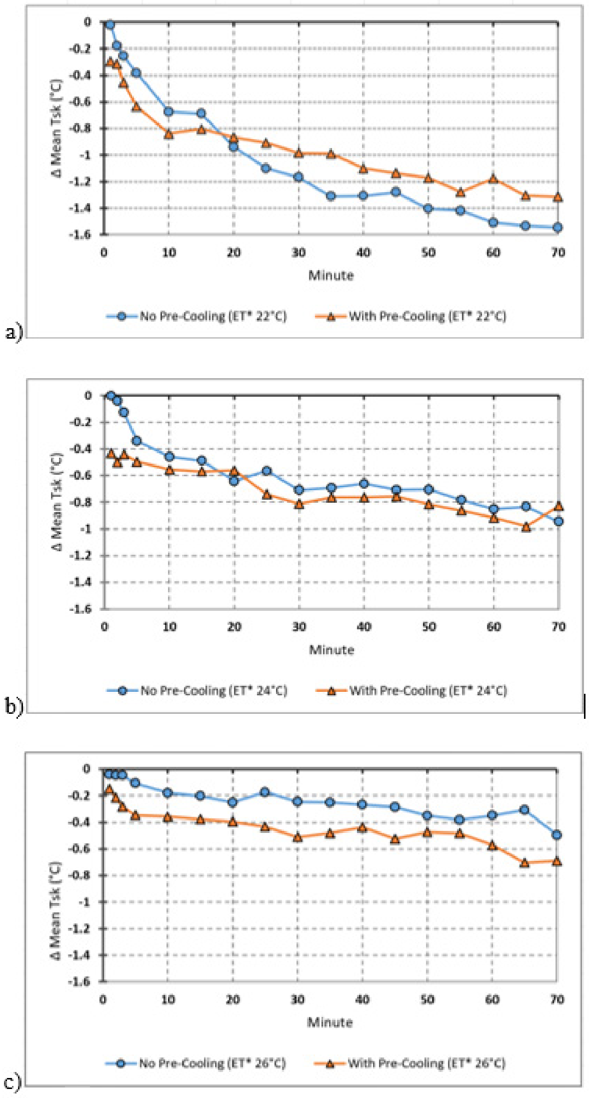

FIGURE 14. Skin temperature differences in pre-cooling and without pre-cooling conditions in (a) stage A, (b) stage B, and (c) stage C.

Figures 15c and 15d show no thermal pleasure detected in both with and without pre-cooling exposures, respectively. It was anticipated that various thermal pleasures would be detected following the onset of *a22*, *a24*, and *a26*; instead, indifferent votes were collected. A one-way ANOVA shows no significant difference in the means for all TSV and ΨPles responses collected from the three stages.

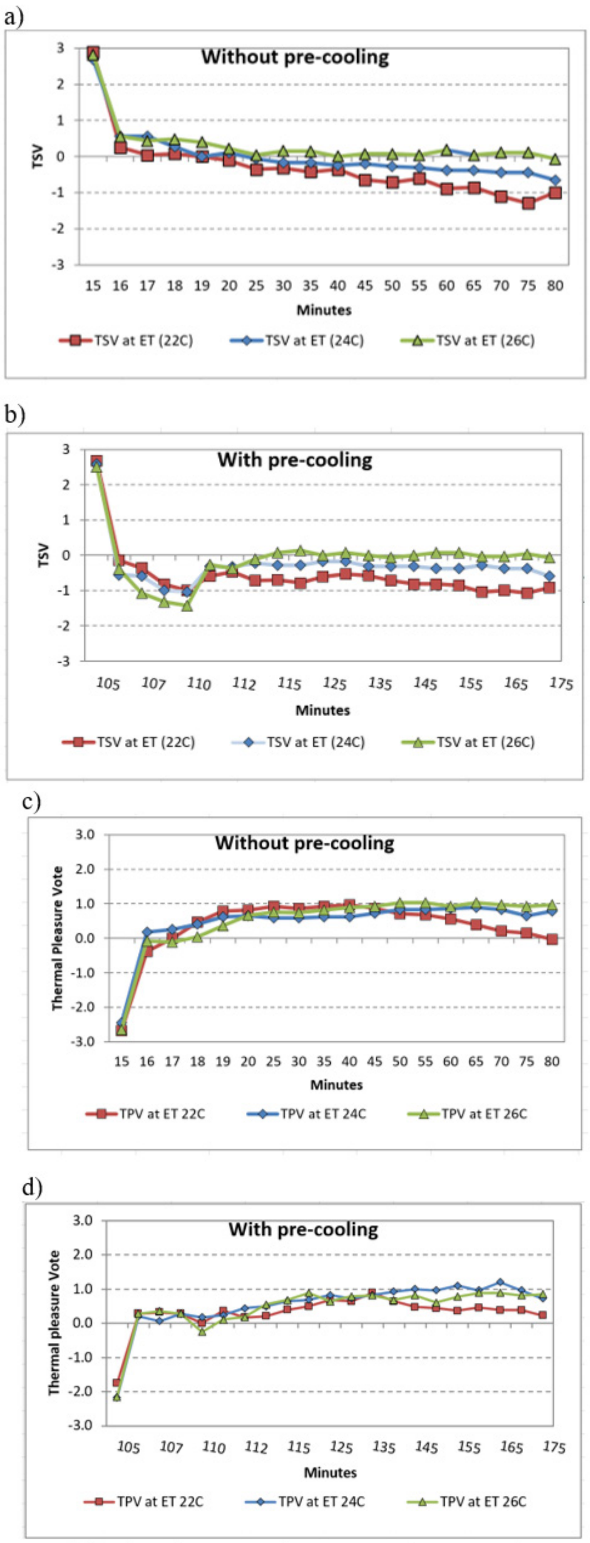

FIGURE 15. TSV (a) and (b) and ΨPles (c) and (d) changes in both pre-cooling conditions. (a) Shows the TSV following the onset of *a22, a24*, and *a26* step-changes; (b) shows TSV following the onset of *e22, e24,* and *e26*; (c) Shows the ΨPles following the onset of *a22, a24,* and *a26* step-changes; and (d) shows ΨPles following the onset of *e22, e24, and e26.*

Pearson correlation suggests that the changes in the skin temperature strongly affect the thermal sensation and thermal pleasure votes with mostly significant differences in the means at the 0.01 level (Table 2). However, surprisingly, changes in skin temperature directly affected the participants' thermal pleasure. These findings suggest that the participants in this experiment did not report pleasure following corrective transitions within the thermoneutral zone. This is in agreement with many thermal comfort studies (Moneim Attia 1984; M. Attia & Engel 1981; Cabanac 1992; Richard. de Dear 2011), which argue that one must be in a state of discomfort to experience positive thermal pleasure during environmental transient conditions.

TABLE 2. Pearson correlation between Δ mean Tsk and thermal perceptions, namely TSV and ΨPles.

n= 18	Pearson Correlations (r)	
	TSV(A) without pre-cool	ΨPles (A) without pre-cool
Δ Mean Tsk(A) without pre-cool	0.75**	0.96**
	TSV(B) without pre-cool	ΨPles (B) without pre-cool
Δ Mean Tsk(B) without pre-cool	0.75**	0.94**
	TSV(C) without pre-cool	ΨPles (C) without pre-cool
Δ Mean Tsk(C) without pre-cool	0.50*	0.94**
	TSV(A) with pre-cool	ΨPles (A) with pre-cool
Δ Mean Tsk(A) with pre-cool	0.68**	0.93**
	TSV(B) with pre-cool	ΨPles (B) with pre-cool
Δ Mean Tsk(B) with pre-cool	0.01	0.85**
	TSV(C) with pre-cool	ΨPles (C) with pre-cool
Δ Mean Tsk(C) with pre-cool	0.27	0.95**

*** Correlation is significant at the 0.01 level (2-tailed).*
** Correlation is significant at the 0.05 level (2-tailed).*

Table 3 shows the paired sample test findings between the thermal sensation and thermal pleasure votes in each experiment group for both exposures of pre-cooling conditions. The most significant difference in means ($p < 0.01$) is between the thermal sensation votes in Stage A. When participants were exposed to non-pre-cooling conditions, they were more likely to feel neutral than slightly cool. Exposure to pre-cooling conditions elicits prolonged slightly cool sensation through the 70 min duration in Chamber 2 (Figure 15). Similarly, in Stage C, a significant difference in means ($p < 0.05$) was observed, where exposure to pre-cooling condition was felt as mostly slightly cool until 5 min immediately after step-change a26. The slightly cool sensation is more prominent in this stage due to the 6 °C difference between the ET* in Chamber 2 and the intermediate space. However, no significant difference in means was detected in Stage B. These results suggest that exposure to pre-cooling conditions close to just the 2 °C temperature difference (in Stage A) produces a negative load error, thereby prolonging the body's heat loss coping mechanism through shivering. Furthermore, participants feel indifferent to the ET* that is close to Tpref, as observed in Stages B and C.

APPLICATION TO THE BUILT ENVIRONMENT

Elevated air temperature settings within 26 -29 °C in air-conditioned spaces have been shown to be healthier and more comfortable. These settings lower the temperature difference between indoor and warm outdoor environments (Lu & Li 2020; Yu et al. 2016; Zhao 2007). The findings of this study indirectly provide the basics for physical activity intervention during working hours: building occupants are encouraged to engage in more non-sedentary tasks by utilising the surrounding built environment while observing a flexible working environment.

In addition, thermal comfort cooling regulations in tropical countries such as the Malaysian Standard (MS1525) (2014), do not regulate the thermal environment of transitional spaces. It focuses on steady-state air-conditioned spaces but provide no specific suggestions on the temperature steps between transient thermal environments. This study provides a potential avenue for the passive design of transitional spaces in buildings and creates an energy-saving and satisfactory built for its occupants.

TABLE 3. Paired sample test findings between thermal sensation and thermal pleasure votes when exposed to both pre-cooling conditions.

Paired Samples Test n=18	95% Confidence Interval of the Difference					
	Mean	S.D	Lower	Upper	t	Sig. (2-tailed)
TSV22(no p.cool) -TSV22(with p.cool)	0.33	±0.9	0.1	0.6	2.915	*p< 0.01*
TSV24(no p.cool) -TSV24(with p.cool)	0.28	±0.8	-1.0	0.7	1.567	*n.s*
TSV26(no p.cool)-TSV26(with p.cool)	0.22	±0.4	0.0	0.4	2.204	*p< 0.05*
ΨPles22(no p.cool)-ΨPles22(with p.cool)	0.05	±0.5	-0.2	0.3	.430	*n.s*
ΨPles24(no p.cool)-ΨPles24(with p.cool)	0.01	±0.2	-0.1	0.1	.212	*n.s*
ΨPles26(no p.cool) -ΨPles26(with p.cool)	0.12	±0.4	-0.1	0.3	1.387	*n.s*

LIMITATIONS

The experiments were conducted in three conjoining chambers to simulate participants' commutes in transient thermal conditions based on three different ET*s. However, the thermocouple tips were occasionally dislocated, particularly at the abdomen and instep. Participants who were observed to perspire heavily also had some issues with the adhesive surgical tapes. Note that an experimenter was present during the procedure to minimise these malfunctions. The decision to conduct a three-hour experiment with four participants in the chambers simultaneously was a necessary decision to maximise the sample size within the resources made available for these experiments. Participants were always reminded not to discuss their votes to reduce data contamination.

CONCLUSION

This study aims to simulate the thermal alliesthesial concept through pre-cooling strategies in tropical commercial buildings by purging surplus body heat, particularly at the entry point of a transitional space. An over-cool transitional space at 20 °C ET* was placed to provide the trigger for peripheral heat loss after exposure to the warm outdoor weather. However, there were a few occurrences of thermal shock that occurred during the down-step transition from 15 min of a mild physical task at 33 °C ET* to the 20 °C ET* pre-cooled intermediate space. A less intense cold stress was observed in the preconditioned 22 °C ET* without additional over-cooling. This suggests that indoor spaces, such as offices and retail shops, should avoid a low indoor air-conditioning set point (i.e., <22 °C ET*) as this can induce thermal shock. A transient environment induced by a large temperature difference down-step, when travelling from a warm outdoor into a preconditioned indoor environment no cooler than 24 °C ET*, may elicit a high level of thermal pleasure in the building occupants. This can eliminate the need to overcool the indoor environment.

Future studies should examine the transient thermal environment in an actual built environment, combined with exercise, food intake, and direct radiation exposure. In addition, the study of the level of perceived alertness and arousal may also be useful in understanding the effects of the thermal transient on flexible working environments.

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DECLARATION OF COMPETING INTEREST

None

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