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Effects of temperature, air movement and initial metabolic rate on thermal sensation during transient state in the tropics

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ABSTRACT

The effects of temperature, air movement and initial metabolic rate on transient thermal sensation at warm temperatures and high humidity among tropically acclimatized people were investigated. 26 tropically acclimatized subjects (13 males and 13 females) participated in the experiments with two different initial metabolic rates at temperatures of 24, 27 and 30 °C, relative humidity (RH) of 60% and air velocities ranging from 0.07 to 1.87 m/s. All the subjects participated in 18 sessions, each for 3.5 h. Thermal sensation in the first few minutes after entering the room moderated earlier with elevated air movement. Thermal sensation, thermal comfort and thermal acceptability reached steady-state within 15 and 25 min respectively at 27 and 30 °C with elevated air movement up to 1.87 m/s even at high initial metabolic rates. Air movement, temperature and initial metabolic rate had a great impact on immediate change in thermal sensation, comfort and acceptability after entry into an air-conditioned room from an outdoor environment. Thermal comfort was highly correlated with thermal sensation during the transient phase and it was observed that a much cooler thermal sensation than in steady-state was necessary for optimal thermal comfort during the transient state. When the initial metabolic rate decreased, the preferred thermal sensation for tropically acclimatized people showed a noticeable shift from cool (−1.87) to slightly cool (−0.77).

1. Introduction

In tropical and subtropical regions, Air-Conditioning (AC) system is employed throughout the year. In this regard, energy conservation of AC system can be seen as a critical strategy towards improving the energy performance of buildings, especially towards realizing the goal of net zero energy buildings in the tropics. Dedicated Outdoor Air System coupled with ceiling fans (DOAS-CF) [1] and Passive Displacement Cooling system (PDC) [2] receive considerable attention now as efficient air-conditioning systems in the tropics. In particular, the DOAS-CF is a simple system, inexpensive for installation and can maintain good indoor air quality due to its ability to deliver 100% outdoor air for ventilation.

Strategies in which the room temperature is raised for energy conservation and air movement created by ceiling fans are used for the improvement of thermal comfort (TC) and Perceived Air Quality (PAQ) in warm environments (27 °C/60% RH) can be quite beneficial. It is to be noted from ASHRAE standard 55–2017 that the acceptable range for thermal comfort can be extended by elevated air movement [3]. In addition, an energy conservation of 17% was estimated using the reduction rate of 5.4%/°C of the National Bureau of Standards using the above strategy [4]. The maximum energy savings by increasing room temperature with elevated air movement reached 48% as reported in simulation case studies in European climate [5]. Energy conservation of this strategy was estimated to 44 kWh/m^{2}yr based on the measured results of office building in Singapore when the room temperature was raised from 23 to 26 °C [6].

Several laboratory studies and field surveys have investigated the positive effect of air movement on thermal comfort in hot and humid conditions. Elevated air movement created by ceiling fans achieved thermal comfort up to 29 °C/50% RH [4,7,8]. However, there may be some issues such as dry eyes and flying paper due to high air speeds. Thermal comfort and PAQ were maintained up to 30 °C/80% RH without dry-eye issues due to the elevated air movement of 1.2 m/s by ceiling fans [9]. Although the cooling effect was different depending on the type of the fans that result in different body regions receiving different air movement [10], there were some studies about the effect of air movement on thermal comfort in hot and humid conditions. An air velocity of 0.35 m/s using floor fans was recommended to keep thermal comfort at operative temperature of 29 °C with 50% RH [11]. Thermal

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comfort was retained by increasing 0.2 m/s of air velocity using floor fans as SET* rose 2 °C [12]. Elevated air movement by individually controlled stand fan improved thermal comfort at 30 °C/60% RH without dry eyes [13]. In the tropical region, Schiavon et al. [14] found that thermal comfort and PAQ were maintained for tropically acclimatized subjects at 29 °C with personalized stand fan. Although the above studies were conducted in the controlled chamber, the effect of air movement provided by ceiling fans on thermal comfort was investigated at an actual office in Singapore [6]. The thermal satisfaction and thermal acceptability at 26 °C with fans were higher than those at 23 °C without fans.

The stated standards [3] and studies [4–14] are only focused on a steady-state condition involving occupants in a steady-state at the given metabolic rate in the range of 1.0–1.3 met. When people enter an air-conditioned room from outdoor, they experience sudden changes in temperature and air movement. In addition, metabolic rate varies depending on the activities such as walking and resting before entering the room. Preferred thermal sensation and air movement sensation may change continuously depending on changes in the metabolic rate after entering into a room because preferred temperature [15] and air movement sensation [16] are influenced by the metabolic rate. Moreover, changes in temperature and air movement affect preferred thermal sensation and air movement sensation due to increasing body heat loss. These factors, such as changes in temperature and air movement and initial metabolic rate, may dynamically affect thermal sensation (TS) until steady-state condition is reached. Human beings control body temperature by autonomous thermoregulation such as vasodilation and sweating and behavioral thermoregulation such as moving from warm to cool environments. Several studies have reported the effect of initial metabolic rate on thermal sensation [17,18]. When body core temperature increases by excess body heat created in response to walking, the heat loss increases due to vasodilation and sweating near the skin, based on the signal from thermoregulatory system in the hypothalamus. It has been reported that thermal sensation and comfort reached steady-state within 20–30 min after exercise at 10, 20 and 30 °C [17]. However, the sample size was only four males. Another study reported that thermal sensation stabilized within 15–20 min after 24 subjects were exposed to metabolic step change from rest (0%) to 20, 40 and 60% of maximum heart rate at moderate temperatures of 21 and 26 °C [18]. However, few studies have examined the effect of initial metabolic rate on thermal sensation in a warm environment. In the case of high initial metabolic rate, thermal sensation may improve rapidly in warm environments compared with low initial metabolic rate when heat loss is accelerated with air movement.

The signal from cutaneous thermoreceptors goes through lateral parabrachial nucleus and encourages behavioral thermoregulation [19]. There have been several studies in the literature reporting the effect of temperature change on thermal sensation, which demonstrated that thermal sensation was changed more quickly than the skin temperature [17,20]. Cold sensation was more accentuated than warm sensation because human beings have cold receptors closer to the skin surface than warm receptors. It was seen that they overestimate thermal sensation when they experience sudden temperature change [21] especially when the temperature difference exceeded 4 °C [22]. When thermoreceptors receive a strong stimulus such as a sudden temperature change above thermoregulatory capacity, thermoregulatory system may not work rapidly. On the other hand, there are very few studies on the effect of air movement on transient thermal sensation. Thermal sensation may reach steady-state condition earlier with elevated air movement in warm environments. Thermal comfort may be achieved earlier by elevated air movement. In the above case, it may be better to change fan speed for thermal comfort continuously depending on the metabolic rate.

A comprehensive human response study focusing on both the transient and steady-state conditions was conducted in a typical seminar room involving the use of a DOAS-CF. We conducted subjective measurements to investigate the effect of temperature, air movement and initial metabolic rate on thermal sensation in warm environments for tropically acclimatized people during the transient phase. The objective of this study is to examine the dynamic characteristics of thermal sensation, comfort and acceptability to temperature, air movement and initial metabolic rate in transient conditions. Each of the experiments involving transient condition was then extended into steady-state condition, the focus of which was to investigate the effect of air movement on thermal comfort and PAQ in warm environments in steady-state conditions. The findings of the steady-state conditions will be the subject of a future paper.

2. Methods

Subjective measurements were conducted to study the effects of temperature, air movement and initial metabolic rate on thermal sensation for tropically acclimatized subjects in warm temperature and high humid conditions in an AC room. The detailed information of the facility is presented in the literature [1].

2.1. Experimental facility

The subjective experiments were conducted in a classroom (5.6 m*7.6 m*4.3 m) at the National University of Singapore (NUS) [1]. The southern windows have the white roller blinds closed to reduce the impact of radiant heat gain. Conditioned outdoor air is supplied to the test room from two square diffusers (0.6 m*0.6 m) at 3.4 m height by an outdoor package AC unit with Variable Air Volume (VAV) boxes. The damper opening of the VAV system was controlled manually for 5 min interval by checking the off-coil temperature and the room temperature and humidity at the perimeter, center and interior of the room to maintain the various room temperature and humidity conditions for the various experimental sessions. A 1.3 m diameter ceiling fan employs a 7-speed controller to regulate air movement (60 RPM-182 RPM). The fan power consumption is from 2 W (60 RPM) to 32 W (182 RPM). The ceiling fans are installed at 2.6 m above the floor level.

2.2. Subjects

26 healthy university subjects (13 males and 13 females), who were acclimatized to the local climate and had lived in Singapore for at least 6 years, participated in 18 experimental sessions. The anthropometric data and clothing insulation of subjects are shown in Table 1. Their ages ranged from 19 to 25 years. Subjects were free to wear the clothes of their choice. Typical clothing includes T-shirt or short-sleeve shirt, shorts or thin pants, undergarments, socks and shoes or sandals (average 0.30 clo). Subjects were seated on typical plastic chairs (about

Table 1
Anthropometric data and clothing insulation of subjects.

Gender	Number	Age (years)	Residence duration in SG (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)	Total clothing value including chair (clo)
Male	13	22.5 ± 1.6	21.2 ± 4.7	172.0 ± 7.5	66.0 ± 6.6	22.4 ± 2.4	0.38 ± 0.08
Female	13	21.2 ± 1.3	19.1 ± 3.9	163.1 ± 6.2	54.9 ± 11.2	20.7 ± 4.4	0.42 ± 0.11
All	26	21.8 ± 1.6	20.1 ± 4.4	167.5 ± 8.2	60.4 ± 10.7	21.5 ± 3.6	0.40 ± 0.10

Table 2
Experimental cases.

- Route 1 (480 m): Round-trip from the test room to restaurant under the shade by walk (5 min). Take rest in front of the room for 10 min and then enter the room.
- Route 2 (960 m): Round-trip from the test room to Bus stop in front of the computer center without the shade by walk (12 min). After walking, enter straight into the room.
- Route 2' (960 m): Round-trip from the test room to Engineering ward 4 under the shade by walk (12 min). After walking, enter straight into the room.

No.	Before entering the room	Temperature in the room [°C]	Ceiling fan speed level
1	Route 1 (AM)	24	Zero (0)-Middle (3) – High (5)
2		27	Zero (0)-Middle (3) – High (5)
3		30	Zero (0)-Middle (3) – High (5)
4	Route 2 (PM) (If it rains, Route 2′)	24	Zero (0)-Middle (3) – High (5)
5		27	Zero (0)-Middle (3) – High (5)
6		30	Zero (0)-Middle (3) – High (5)

0.10 clo), normally used in classrooms. The total clothing value including chair insulation was 0.40 clo. Medication and alcohol intake were not allowed within 24 h before the experiment. Informed consent was obtained from each subject. All protocols were approved by NUS Institutional Review Board. All subjects were volunteers and were monetarily compensated for their participation in the experiments.

2.3. Experimental design

2.3.1. Experimental conditions

The study was conducted from 11th December 2017 to 15th February 2018. All 26 subjects participated in 18 experimental sessions, generating a total of 468 experimental data points. Each experimental session was conducted in the morning and the afternoon on weekdays and lasted for 3 h and 30 min. The morning sessions were conducted from 9 a.m. to 12:30 p.m. and the afternoon sessions from 2 p.m. to 5:30 p.m. The parameters of the experiments were initial metabolic rate conditions before entering the room, room temperature and ceiling fan speed mode (Table 2). There were two routes for outdoor walking to simulate two initial metabolic rates experienced by students (Fig. 1). In the morning session (Route 1: 480 m), subjects walked a round-trip from the test room under the shade to a nearby restaurant for 5 min to simulate a short walk. In the afternoon session (Route 2: 960 m), they walked a round-trip from the test room without shade to a nearby bus stop in front of the Computer Center for 12 min to simulate a long walk. If it rained, Route 2' (960 m) of a round-trip walking from the test room under the shade to a nearby Faculty of Engineering ward 4 for 12 min was conducted instead of Route 2. Unknown to the subjects, the room temperature was changed every week and the order of the ceiling fan speed mode was changed every 3 weeks (0-3-5 from Week 1–3, 5-3-0 from Week 4–6 and 3-5-0 from Week 7–9).

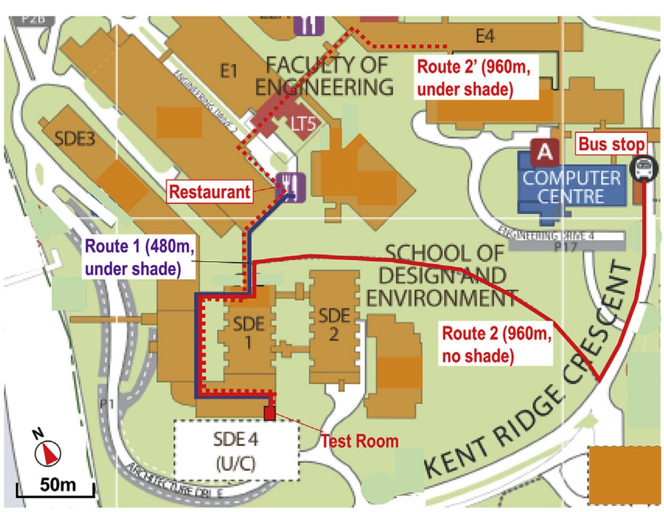


Fig. 1. Experimental session walking routes in National University of Singapore.

2.3.2. Experimental procedure

The experimental procedure is shown in Fig. 2. Subjects first completed a questionnaire about their background information such as gender, age, height, health condition and clothes.

A Subjects were asked to walk outdoors for a maximum of 12 min as guided by the researcher to achieve the metabolic rate commensurate with the two walking activities typical with students at the university.

B After walking, subjects took rest for 10 min in front of the test room and then spent about 30 s to complete the short survey questionnaire in Route 1. The 10-min rest in Route 1 (representative of low initial met rate) was incorporated as part of the experimental protocol to offer some level of acclimatization with the outdoor environment before the subjects entered the test room. However, in Route 2 (representative of high initial met rate), acclimatization with the outdoor environment was not permitted and the subjects answered a short questionnaire and then entered the test room directly. The body weight was measured before entering the room.

C After entering the test room, subjects stayed for 45 min and answered a questionnaire about their thermal sensation, and this was done 7 times in total. They were allowed to read books or engage in sedentary tasks during this time but not to stand up, walk around the room, sleep, eat or drink. Finally, the body weight was measured before they left the session to obtain an estimate of latent heat loss. They took a 10-min break at each hour outside for acclimation with outdoor environment and were only allowed to drink during the break.

This procedure of A to C was repeated three times under different fan speed modes. Subjects answered a short questionnaire before and after walking and at the 1st, 2nd, 5th, 20th and 30th minute, and a long questionnaire at 10th and 40th minute. They were asked to sit in seats that were fixed in position on the floor by adhesive tape so that each subject sitting in the same seat receives the same air flow provided by the ceiling fan. They were not informed of the experimental conditions.

2.4. Data collection

Four desks and chairs were located right under each ceiling fan so that the occupants would receive air flow as uniformly as possible in the test room (Fig. 3). Air temperature was measured at 5 min interval using Type-T thermocouple wires possessing an accuracy of ± 0.5 °C of reading at the heights of 0.1, 0.6, 1.1, 1.7 and 2.2 m, which include locations corresponding to the ankle, body and head for a sedentary person [3]. Globe temperature was measured using the globe thermometer and Type-T thermocouple wires for 5 min interval at 1.1 m. Relative humidity was measured at 5 min interval by HIOKI logger (an accuracy of ± 3% of reading) at 1.1 m. These measurement points are

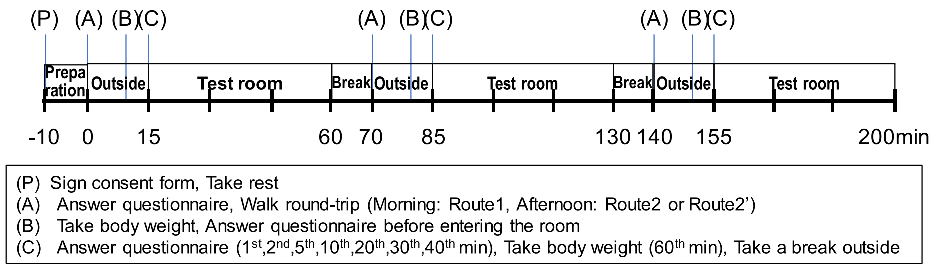


Fig. 2. Experimental procedure.

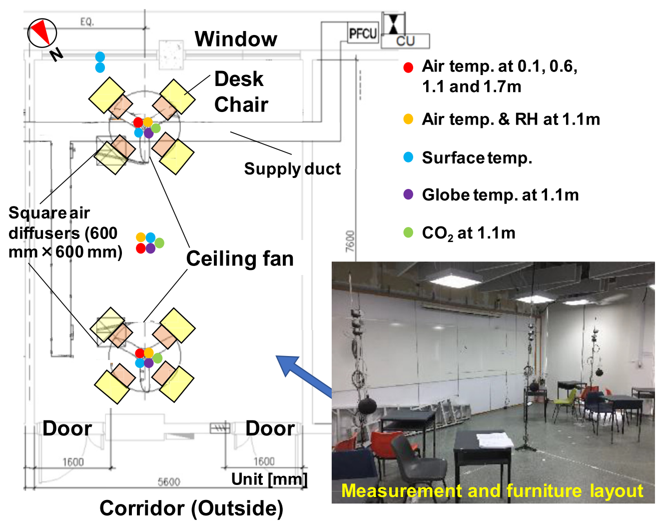


Fig. 3. Experimental facility and the location of the instruments.

at the center of the room and under the ceiling fans (Fig. 3). Average air velocity (sampled at 1 s interval for 3 min) was obtained by spot measurements, using omnidirectional anemometer (an accuracy of ± 0.1 m/s) at the heights of 0.1, 0.6, 1.1 and 1.7 m at each seat before subjects occupied the room. The body weight was measured before and after the sessions with an accuracy of ± 50 g of reading to establish the amount of moisture lost.

2.5. Questionnaire

Table 3 shows the outline of questionnaire, commonly adopted in thermal comfort research [3,9,14]. Subjects answer two kinds of questionnaires. The short questionnaire includes 6 questions: (1) thermal sensation (TS); (2) thermal comfort (TC); (3) thermal acceptability (TA); (4) air movement acceptability; (5) air movement preference; and (6) sweating condition. The long questionnaire that relates to the steady-state analysis includes all questions, as shown in Table 2. As mentioned earlier, the steady-state analysis will be the subject of another paper in the future.

2.6. Data analysis

The subjective results are analysed using Microsoft Excel Analysis ToolPak. The data is analysed by statistical approaches. In transient conditions, the differences in subjective votes between ambient temperatures, fan speed modes and initial metabolic rates are analysed by Kruskal-Wallis test followed by the Steel-Dwass procedure for multiple comparisons. The box plots are used for the analysis of the data distribution of subjective votes. The median value (25th percentile, 75th percentile) are shown in the following results. The statistical significance is considered when $p < 0.05$. Subjective votes are fitted by non-linear least squares approximation to analyse the stabilized time (Eq. (1)) as used by previous researchers [18,21,23].

$$y = A + B \cdot \exp(-t/\tau) \tag{1}$$

Where y is the predicted subjective vote, A and B are coefficients, t is the elapsed time after entering the test room [min], τ is the time constant [min].

Equation (1) is used for the time series results of increasing and decreasing subjective votes. Subjective vote is considered to reach steady-state when it reaches 95% of the change. This is the stabilized time, corresponding to 3τ.

3. Results

3.1. Test conditions

Table 4 shows the indoor target and measured temperature, globe temperature and RH. The measured values are the average values at 1.1 m height at the center of the room and under the ceiling fans. The temperature and RH conditions were controlled close to the target value of ± 0.5 °C and ± 5%, respectively. The differences between air temperatures and globe temperatures were small within 0.4 °C because of the closed roller blinds. The vertical temperature differences between 0.1 and 1.7 m were less than 0.5 °C at each condition. Table 5 shows average air velocity at each seat. In Mode 0 (M0), air velocity was from 0.06 to 0.15 m/s at each height. The average turbulence intensity (Tu) was 58%. In Mode 3 (M3), air velocity was from 0.66 to 0.94 m/s at the height of 0.1–1.1 m for sedentary occupants. Tu was around 15%. In Mode 5 (M5), air velocity was around 1.25 m/s at 0.1 and 0.6 m and 1.87 m/s at 1.1 m around the head region for sedentary occupants. Tu was about 14%.

Table 6 shows average outdoor environmental conditions during morning and afternoon walking and temperature differences between outdoor and indoor conditions. Each test condition was conducted 12 times. In the morning, the outdoor temperature of 26.3 °C (corresponding to the set of experiment when the indoor set point temperature was set at 24 °C) was cooler than other conditions because four out of the five days had overcast and rainy conditions in early January 2018. In the afternoon, the outdoor temperature of 29.0 °C (corresponding to the set of experiment when the indoor condition was set at 30 °C) was higher than other conditions because approximately 80% of the experimental days were sunny. Specific enthalpies in the morning were also lower than those in the afternoon. When subjects entered the test room at 24 °C, they experienced a temperature step-down between 2 and 3 °C. The temperature differences between indoor and outdoor were less than 1 °C at 27 °C. Subjects experienced a temperature step-up from 1.1 to 2.4 °C at 30 °C.

3.2. Transient responses

In this section, the effects of temperature, air movement and initial metabolic rate on thermal sensation are analysed. In addition, the representative air velocity at 1.1 m is described at each fan speed mode in the following sections.

Table 3
Outline of questionnaire.

Category	Question	Scale and contents	Short Q	Long Q
Thermal comfort	Thermal sensation	7-scale (−3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot)	○	○
	Thermal preference	5-scale (−2 much cooler, −1 slightly cooler, 0 no change, +1 slightly warmer, +2 warmer		○
	Thermal comfort	(-2 very uncomfortable, −1 uncomfortable, −0.1 slightly uncomfortable, +0.1 slightly comfortable, +1 comfortable, +2 very comfortable) * divided at the center point	○	○
	Thermal acceptability	(-1 clearly unacceptable, −0.1 just unacceptable, +0.1 just acceptable, +1 clearly acceptable) * divided at the center point	○	○
Humidity	Humidity sensation	7-scale (−3 very humid, −2 humid, −1 slightly humid, 0 neutral, +1 slightly dry, +2 dry, +3 very dry)		○
	Humidity acceptability	(-1 clearly unacceptable, −0.1 just unacceptable, +0.1 just acceptable, +1 clearly acceptable) * divided at the center point		○
Air movement	Air movement sensation	7-scale (−3 very low, −2 low, −1 slightly low, 0 neutral, +1 slightly high, +2 high, +3 very high)		○
	Air movement acceptability	(-1 clearly unacceptable, −0.1 just unacceptable, +0.1 just acceptable, +1 clearly acceptable) * divided at the center point	○	○
	Air movement preference	5-scale (−2 much less, −1 slightly less, 0 no change, +1 slightly more, +2 much more	○	○
Sweat	Sweating	4-point scale (0 no sweating, +1 slightly, +2 moderate, +3 profusely)	○	○
Indoor air quality (IAQ)	Indoor air quality acceptability	(-1 clearly unacceptable, −0.1 just unacceptable, +0.1 just acceptable, +1 clearly acceptable) * divided at the center point		○
	Air freshness	Continuous scale from air stuffy (0) to air freshest (100)		○
Odor	Odor intensity	5- scale (0 no, +1 light, +2 moderate, +3 strong, +4very strong)		○
Dry-eye	Dry-eye discomfort	(-1 clearly unacceptable, −0.1 just unacceptable, +0.1 just acceptable, +1 clearly acceptable) * divided at the center point		○

Table 4
Indoor target and measured temperature, globe temperature and RH.

Target		Ceiling fan speed [0–6]	Measured		
T [°C]	RH [%]		T [°C]	RH [%]	Globe T [°C]
24	60	0 (OFF)	24.0 ± 0.17	61.8 ± 1.0	24.4 ± 0.13
24	60	3 (Middle)	24.0 ± 0.14	61.9 ± 1.0	24.3 ± 0.13
24	60	5 (High)	24.2 ± 0.16	61.3 ± 0.9	24.3 ± 0.14
27	60	0	27.0 ± 0.20	62.1 ± 2.2	27.3 ± 0.18
27	60	3	26.9 ± 0.17	61.4 ± 1.9	27.2 ± 0.13
27	60	5	27.1 ± 0.20	61.3 ± 1.9	27.3 ± 0.10
30	60	0	30.0 ± 0.17	60.8 ± 1.6	30.3 ± 0.11
30	60	3	30.0 ± 0.18	60.8 ± 1.3	30.2 ± 0.11
30	60	5	30.1 ± 0.18	60.3 ± 1.4	30.2 ± 0.06

Table 5
Average air velocity at each seat.

	Air velocity [m/s]				Turbulence intensity [%]			
Height [m]	0.1 m	0.6 m	1.1 m	1.7 m	0.1 m	0.6 m	1.1 m	1.7 m
Mode 0 (Off)	0.15	0.06	0.07	0.08	39.4	80.9	54.3	50.5
Mode 3 (Middle)	0.70	0.66	0.94	1.12	15.2	15.7	16.0	16.0
Mode 5 (High)	1.24	1.25	1.87	2.01	15.2	14.7	12.4	13.8

3.2.1. Effect of temperature

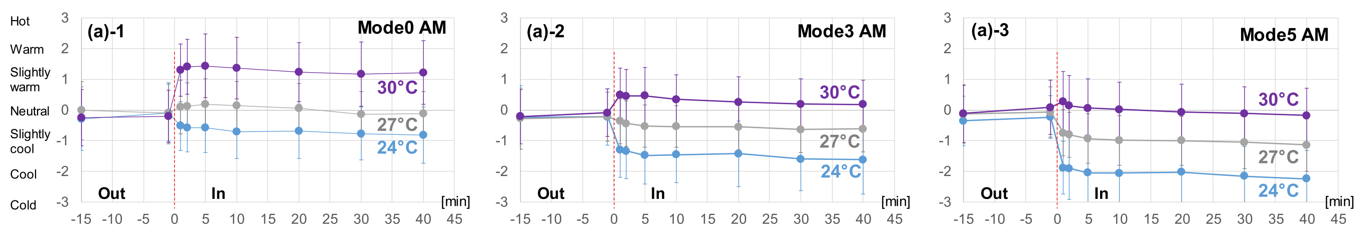
The effects of temperature on thermal sensation (TS), thermal comfort (TC) and thermal acceptability (TA) are compared among 24, 27 and 30 °C in the AM sessions, as shown in Fig. 4. The corresponding statistical analysis for each plot of the three different fan speed modes is presented in the respective tables below the plots. TS votes were clearly different depending on temperatures at each fan speed mode during transient state (Fig. 4(a)). It is observed that temperature affected TS significantly during the transient phase because the differences in TS between 24 and 27 °C ($p < 0.001$), 24 and 30 °C ($p < 0.001$) and, 27 and 30 °C ($p < 0.001$) were statistically significant at each fan speed mode. The positive effect of air movement in improving TC at warmer temperatures is clearly seen from Fig. 4(b). By the same token, increased air movement at a lower temperature of 24 °C had an adverse effect on TC as it tended to shift towards "slightly uncomfortable" region due to cold sensation. The observations of temperature effect on TA with and without air movement are similar to that of TC. It is seen that the TC and TA votes at warmer temperatures (27 and 30 °C) and fan speeds of M0 and M3 are statistically significant, as seen in Fig. 4(b) and (c).

3.2.2. Effect of air movement

The effects of air movement on TS, TC and TA are investigated by a comparison among fan speed modes in the AM sessions (Fig. 5). The results of statistical analysis for the three different fan speeds at each indoor temperature setting are shown in the respective tables below each of the temperature plots. TS votes were different depending on "with or without air movement" during the transient phase (Fig. 5(a)). Significant differences attributed to fan speed modes in TS were observed between M0 and M3 ($p < 0.001$), and M0 and M5 ($p < 0.001$) at each indoor temperature setting. Thermal sensation was close to thermal neutrality at 27 °C with M0, and at 30 °C with M5 over time (Figs. 5(a)-2 and (a)-3). Thermal sensation in the first few minutes after entering the room moderated earlier with elevated air movement. Although TC votes moved to uncomfortable side gradually at 24 °C with M5, air movement of M3 and M5 improved TC votes at warmer temperatures of 27 and 30 °C (Figs. 5(b) and (c)). The trends of the effect of air movement on TA were similar to those of TC at each indoor temperature setting. It is observed that there were significant differences in TC and TA attributed to fan speed modes between M0 and M3 ($p < 0.001$) and, M0 and M5 ($p < 0.001$) in the AM sessions at 30 °C. This is attributed to the differences of TC and TA votes between "with"

Table 6
Outdoor environment during walking and temperature differences between outdoor and indoor.

Test conditions		T [°C]	RH [%]	Specific Enthalpy [kJ/kg]	△t (OA-IA) [°C]		
					Ave.	Max	Min
24°C	AM	26.3 ± 1.2	75.3 ± 4.1	67.2 ± 2.5	2.0	4.2	−1.4
	PM	27.2 ± 1.3	73.0 ± 5.3	69.2 ± 2.8	3.0	5.4	−0.8
27°C	AM	27.2 ± 1.1	70.0 ± 4.7	67.2 ± 2.3	0.1	2.0	−2.4
	PM	27.8 ± 1.1	67.5 ± 5.9	68.0 ± 1.5	0.7	2.5	−1.5
30°C	AM	27.7 ± 0.58	69.8 ± 3.9	69.1 ± 2.6	−2.4	−1.3	−3.8
	PM	29.0 ± 0.62	66.3 ± 5.1	71.1 ± 2.2	−1.1	−0.2	−2.5



Mode 0 AM — * p<0.05, ** p<0.01

	1min	2min	5min	10min	20min	30min	40min
24-27 °C	0.003 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
24-30 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
27-30 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **

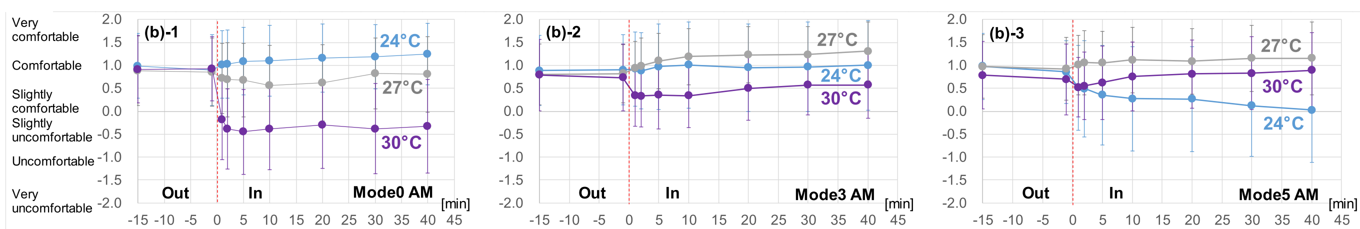
Mode 3 AM

	1min	2min	5min	10min	20min	30min	40min
24-27 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
24-30 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
27-30 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **

Mode 5 AM

	1min	2min	5min	10min	20min	30min	40min
24-27 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
24-30 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
27-30 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **

(a) Thermal sensation (TS)



Mode 0 AM — * p<0.05, ** p<0.01

	1min	2min	5min	10min	20min	30min	40min
24-27 °C	0.935	0.935	0.114	0.014 *	0.020 *	0.256	0.054
24-30 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
27-30 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **

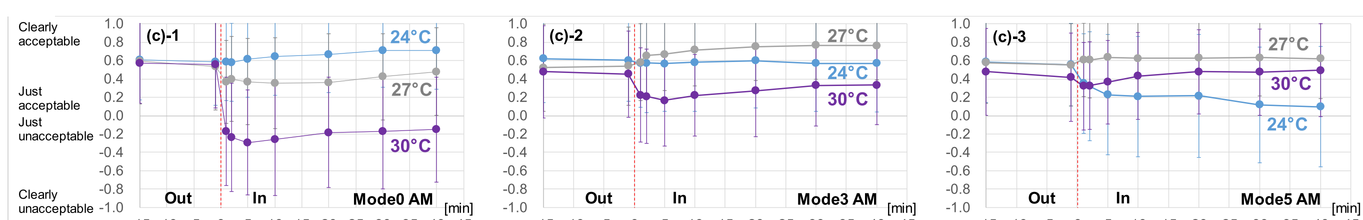
Mode 3 AM

	1min	2min	5min	10min	20min	30min	40min
24-27 °C	1.000	1.000	1.000	1.000	0.970	0.998	0.974
24-30 °C	0.003 **	0.006 **	<0.001 **	<0.001 **	0.056	0.091	0.089
27-30 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **

Mode 5 AM

	1min	2min	5min	10min	20min	30min	40min
24-27 °C	0.052	0.028 *	0.003 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
24-30 °C	1.000	1.000	0.991	0.544	0.183	0.004 **	<0.001 **
27-30 °C	<0.001 **	0.002 **	0.029 *	0.180	0.678	0.390	0.805

(b) Thermal comfort (TC)



Mode 0 AM — * p<0.05, ** p<0.01

	1min	2min	5min	10min	20min	30min	40min
24-27 °C	0.386	0.655	0.053	0.020 *	0.030 *	0.019 *	0.179
24-30 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
27-30 °C	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **

Mode 3 AM

	1min	2min	5min	10min	20min	30min	40min
24-27 °C	1.000	1.000	0.999	0.992	0.944	0.563	0.505
24-30 °C	0.008 **	0.002 **	0.001 **	<0.001 **	0.014 *	0.215	0.162
27-30 °C	0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **

Mode 5 AM

	1min	2min	5min	10min	20min	30min	40min
24-27 °C	0.112	0.115	0.004 **	0.003 **	0.007 **	<0.001 **	<0.001 **
24-30 °C	1.000	1.000	1.000	0.778	0.545	0.015 *	0.017 *
27-30 °C	0.009 **	0.018 *	0.008 **	0.338	0.776	0.782	0.987

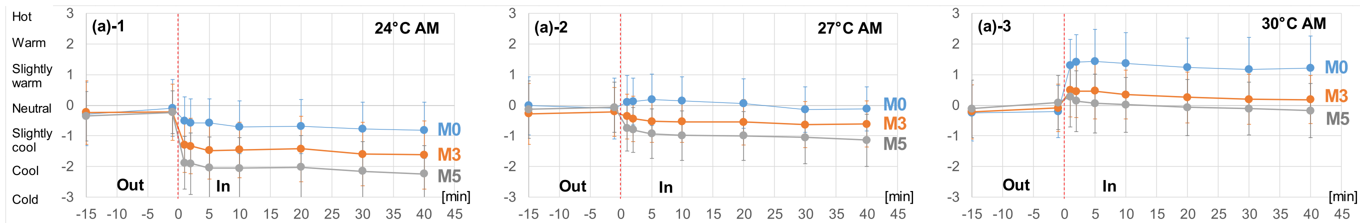
(c) Thermal acceptability (TA)

Fig. 4. Comparisons of thermal sensation, thermal comfort and thermal acceptability votes among indoor temperature settings (24, 27 and 30 °C) at each fan speed mode (Mode 0, Mode 3 and Mode 5). Numbers in the table are p-values indicating significance of statistical difference between the respective compared scenarios.

and "without air movement" that increased as temperature rose.

3.2.3. Effect of initial metabolic rate

The effects of initial metabolic rate on TS, TC and TA are analysed by a comparison between the AM and PM votes (Fig. 6). The statistical analysis for different initial metabolic rates at each indoor temperature setting is described in the respective tables below the plots. TS votes in the PM sessions were warmer than those in the AM sessions in the first few minutes after entering the room because of high initial metabolic rate, and then got closer to the AM votes due to moderation or the gradual alleviation of the adverse effect of the metabolic rate. TS votes at M5 moderated earlier than those at M0 after entering the room at



24°C AM — * p<0.05, ** p<0.01

	1min	2min	5min	10min	20min	30min	40min
M0-M3	<0.001 **	<0.001 **	<0.001 **	<0.001 **	0.003 **	<0.001 **	0.002 **
M0-M5	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
M3-M5	0.023 *	0.048 *	0.042 *	0.016 *	0.053	0.075	0.062

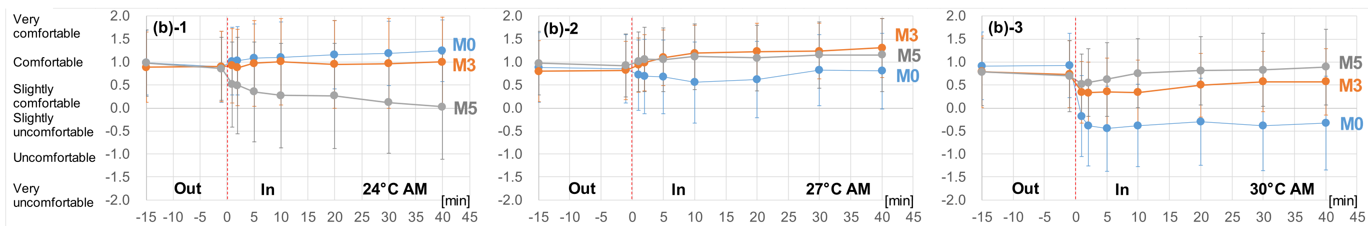
27°C AM

	1min	2min	5min	10min	20min	30min	40min
M0-M3	0.093	0.012 *	<0.001 **	<0.001 **	0.001 **	0.012 *	0.014 *
M0-M5	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
M3-M5	0.211	0.238	0.104	0.083	0.075	0.192	0.015 *

30°C AM

	1min	2min	5min	10min	20min	30min	40min
M0-M3	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
M0-M5	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
M3-M5	0.995	0.823	0.482	0.667	0.643	0.769	0.468

(a) Thermal sensation (TS)



24°C AM — * p<0.05, ** p<0.01

	1min	2min	5min	10min	20min	30min	40min
M0-M3	1.000	1.000	1.000	1.000	1.000	1.000	0.999
M0-M5	0.038 *	0.055	0.002 **	0.001 **	<0.001 **	<0.001 **	<0.001 **
M3-M5	0.445	0.577	0.055	0.012 *	0.038 *	<0.001 **	<0.001 **

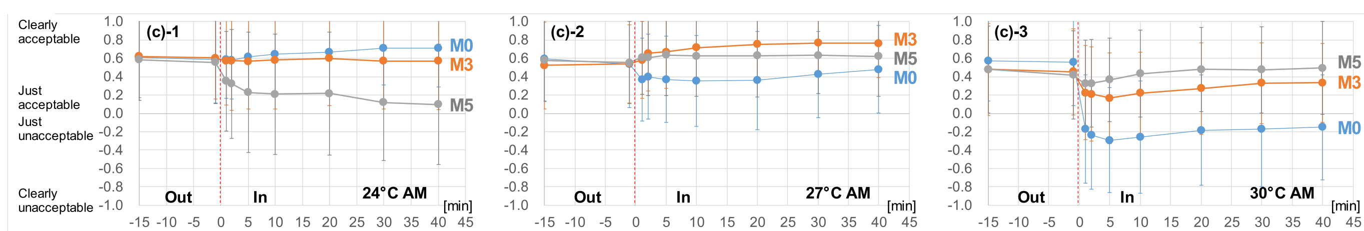
27°C AM

	1min	2min	5min	10min	20min	30min	40min
M0-M3	0.992	0.940	0.025 *	<0.001 **	<0.001 **	0.054	0.008 **
M0-M5	0.915	0.644	0.140	0.003 **	0.041 *	0.394	0.324
M3-M5	1.000	1.000	1.000	1.000	0.998	1.000	1.000

30°C AM

	1min	2min	5min	10min	20min	30min	40min
M0-M3	0.005 **	0.004 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
M0-M5	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
M3-M5	0.996	0.987	0.928	0.085	0.441	0.826	0.573

(b) Thermal comfort (TC)



24°C AM — * p<0.05, ** p<0.01

	1min	2min	5min	10min	20min	30min	40min
M0-M3	1.000	1.000	1.000	1.000	1.000	0.942	0.954
M0-M5	0.195	0.167	0.008 **	<0.001 **	0.001 **	<0.001 **	<0.001 **
M3-M5	0.483	0.256	0.136	0.022 *	0.062	0.001 **	0.002 **

27°C AM

	1min	2min	5min	10min	20min	30min	40min
M0-M3	0.486	0.114	0.004 **	<0.001 **	<0.001 **	<0.001 **	0.013 *
M0-M5	0.136	0.427	0.021 *	0.028 *	0.118	0.322	0.958
M3-M5	1.000	1.000	1.000	0.997	0.966	0.863	0.751

30°C AM

	1min	2min	5min	10min	20min	30min	40min
M0-M3	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
M0-M5	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
M3-M5	1.000	0.998	0.773	0.315	0.245	0.743	0.674

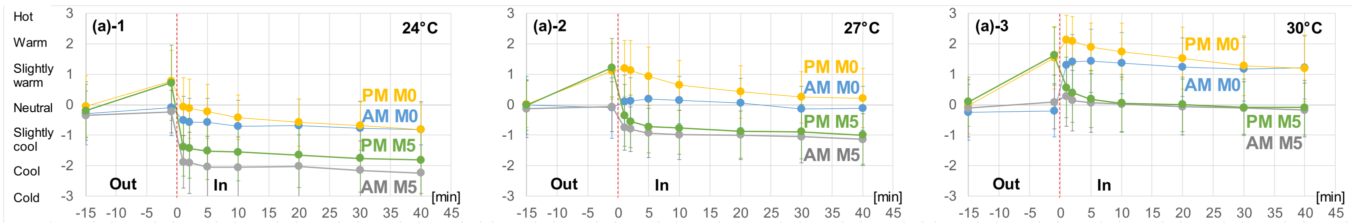
(c) Thermal acceptability (TA)

Fig. 5. Comparisons of thermal sensation, thermal comfort and thermal acceptability votes among fan speed modes (Mode 0, Mode 3 and Mode 5) at each indoor temperature setting (24, 27 and 30 °C). Numbers in the table are p-values indicating significance of statistical difference between the respective compared scenarios.

each indoor temperature setting indicating the positive effect arising from elevated air movement. The initial metabolic rate did not affect TS votes at 24 °C because there was no significant difference between the AM and PM sessions at 24 °C (Fig. 6(a)-1). Since the differences in TS attributed to initial metabolic rate between the AM and PM sessions were observed until 5 min at each indoor temperature setting, it is inferred that the effect of initial metabolic rate on TS was moderated within 10 min at each indoor temperature setting. TC votes in the PM sessions show lower satisfaction than those in the AM sessions after entry into the room due to high initial metabolic rate, and then reached similar satisfaction levels within 10 min because of the moderation effect of the metabolic rate (Fig. 6(b)). TC votes in the first few minutes after entering the room also moderated earlier with elevated air movement. The effects on TA votes are similar to that of TC.

3.2.4. Stabilized time for thermal response

The details of the computed stabilized times of TS, TC and TA votes are presented in Table 7 and Fig. 7. The stabilized times in TS were almost within 15 min except in the AM session at 27 °C with M0 and at 30 °C with M5, and the PM session at 27 and 30 °C with M0 (Fig. 7(a)). Although the stabilized times of 955 min at 27 °C with M0 and 29.2 min at 30 °C with M5 in the AM sessions were longer than 15 min, this has negligible practical importance because TS votes were almost at thermal neutrality from 1st outdoor to 7th votes (Fig. 4(a)). It took shorter time to stabilize TS at higher air speeds except in the AM sessions at 30 °C. The stabilized times of TS were long at warmer temperatures except in the AM session at 30 °C. TC and TA reached steady-state within 25 min with M3 and M5 except in the AM session at 30 °C with M5 and the PM session at 24 °C with M5 (Fig. 7 (b) and (c)). Although the stabilized times of TC and TA in the AM sessions at 30 °C with M5 were longer than 25 min, this was considered relatively insignificant as the sensations were near thermal neutrality. At 24 °C with M5, the stabilized times of TC and TA were rather large at 1438 and 397 min respectively as both TC and TA votes went towards slightly comfortable side gradually. It could be inferred that high air speed at 24 °C was not quite beneficial and was turning out to be



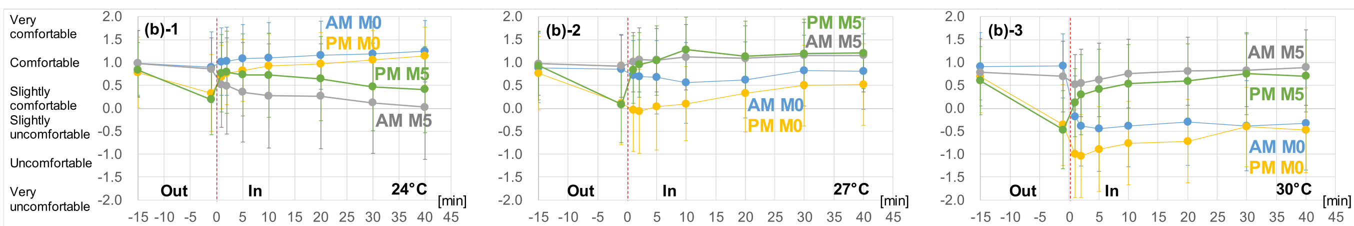
24°C	1min	2min	5min	10min	20min	30min	40min
M0	0.102	0.164	0.446	0.807	1.000	1.000	1.000
M5	0.159	0.241	0.055	0.094	0.659	0.726	0.575

* p<0.05, ** p<0.01

27°C	1min	2min	5min	10min	20min	30min	40min
M0	<0.001 **	<0.001 **	<0.001 **	0.060	0.536	0.360	0.811
M5	0.614	0.981	0.995	0.938	1.000	0.999	0.999

30°C	1min	2min	5min	10min	20min	30min	40min
M0	<0.001 **	<0.001 **	0.298	0.604	0.929	1.000	1.000
M5	0.823	0.987	1.000	1.000	1.000	1.000	1.000

(a) Thermal sensation (TS)



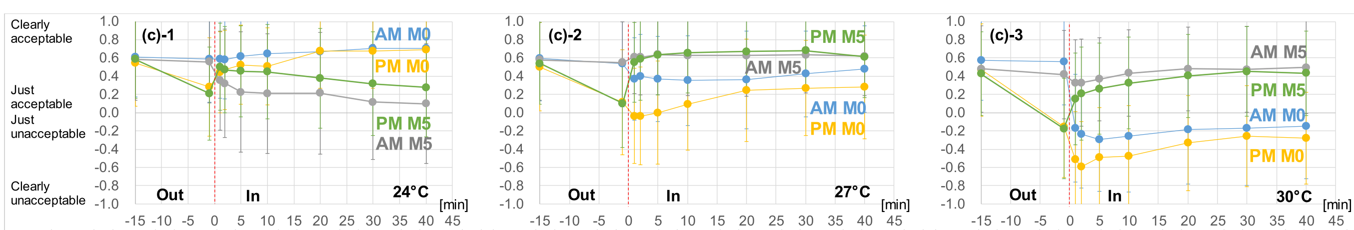
24°C	1min	2min	5min	10min	20min	30min	40min
M0	0.189	0.189	0.715	0.992	0.991	1.000	1.000
M5	0.963	0.901	0.684	0.676	0.876	0.948	0.837

* p<0.05, ** p<0.01

27°C	1min	2min	5min	10min	20min	30min	40min
M0	<0.001 **	<0.001 **	0.001 **	0.084	0.786	0.663	0.810
M5	0.995	1.000	1.000	0.997	1.000	1.000	1.000

30°C	1min	2min	5min	10min	20min	30min	40min
M0	<0.001 **	<0.001 **	0.291	0.604	0.497	1.000	1.000
M5	0.116	0.856	0.998	0.981	0.917	1.000	0.990

(b) Thermal comfort (TC)



24°C	1min	2min	5min	10min	20min	30min	40min
M0	0.715	0.955	0.998	0.890	1.000	1.000	1.000
M5	0.950	0.989	0.702	0.679	0.995	0.865	0.966

* p<0.05, ** p<0.01

27°C	1min	2min	5min	10min	20min	30min	40min
M0	<0.001 **	<0.001 **	0.003 **	0.092	0.997	0.894	0.882
M5	1.000	1.000	1.000	1.000	1.000	1.000	1.000

30°C	1min	2min	5min	10min	20min	30min	40min
M0	0.016 *	0.015 *	0.698	0.860	0.983	1.000	1.000
M5	0.874	0.999	1.000	1.000	1.000	1.000	1.000

(c) Thermal acceptability (TA)

Fig. 6. Comparisons of thermal sensation, thermal comfort and thermal acceptability votes among initial metabolic rates at each indoor temperature setting (24, 27 and 30 °C) at fan speed modes of Mode 0 and 5. Numbers in the table are p-values indicating significance of statistical difference between the respective compared scenarios.

counterproductive. TC and TA reached steady-state early at higher air speeds in the PM session with 27 and 30 °C. Therefore, thermal responses reached steady-state early at higher air speeds. The stabilized times of TS was within 15 min and those of TC and TA were within 25 min at 27 and 30 °C with elevated air movement.

3.2.5. Immediate changes in thermal response

Immediate changes in thermal responses were the differences between 2nd outdoor and 1st indoor votes after entry into the test room (equal to 1 min before and after the points (C) in Fig. 2 (15, 85 and 155 min)), as shown in Fig. 8. The Y-axis describes the differences in thermal response between 1st indoor and 2nd outdoor votes, which is essentially the value obtained by subtracting the 2nd outdoor votes from the 1st indoor votes. The respective tables below the box plots show the statistical analysis for temperatures, fan speed modes and initial metabolic rates. It is seen that air speed resulted in cooler TS; the larger the air speed, the larger the cooling TS effect. (Fig. 8(a)). Significant differences in TS attributed to fan speed modes between M0 (0.07 m/s) and M5 (1.87 m/s) were found at each indoor temperature setting ($p < 0.001$). The immediate changes in TS moved to cooler side at lower temperatures. The immediate changes in TS were significantly different between 24 and 30 °C ($p < 0.001$) at each fan speed mode. The immediate changes in TS in the PM sessions were larger (cooler) than those in the AM sessions between the same temperatures and the same fan speed modes. Comparing the corresponding fan and setpoint scenarios between the AM and PM sessions, it is observed that the differences in TS due to initial metabolic rate were statistically significant at 27 and 30 °C with M3 and M5 ($p < 0.001$).

The immediate changes in TC went towards comfortable side at higher air speeds except in the AM sessions with 24 °C (Fig. 8(b)). Significant differences in TC due to fan speed modes between M0 and M3 ($p < 0.001$), and M0 and M5 ($p < 0.001$) were observed in the AM sessions with 30 °C and in the PM sessions with 27 and 30 °C. The immediate changes in TC moved to comfortable side at higher initial metabolic rate for the same temperatures and the same fan speed modes. There were significant differences in TC attributed to initial

Table 7
Coefficient of non-linear regression model and stabilized time of thermal responses.

			Thermal sensation					Thermal comfort					Thermal acceptability				
			A	B	τ[min]	3τ[min]	R^2	A	B	τ[min]	3τ[min]	R^2	A	B	τ[min]	3τ[min]	R^2
24°C	AM	M0	-0.74	0.63	2.3	7.0	0.936	1.22	-0.28	10.0	29.9	0.925	0.75	-0.17	25.3	75.8	0.967
		M3	-1.51	1.28	1.3	3.8	0.976	0.98	-0.10	5.5	16.4	0.582	0.58	0.03	0.1	0.4	0.455
		M5	-2.10	1.87	1.0	3.1	0.985	0.14	0.67	4.9	14.8	0.918	0.15	0.39	3.5	10.6	0.931
	PM	M0	-0.63	1.33	3.4	10.1	0.921	1.04	-0.67	4.0	11.9	0.936	0.68	-0.36	8.4	25.3	0.912
		M3	-1.05	1.95	1.4	4.2	0.982	1.16	-1.12	1.6	4.9	0.983	0.67	-0.57	1.3	3.8	0.972
		M5	-1.66	2.37	1.0	3.0	0.984	-4.06	4.87	479.5	1438	0.955	-0.36	0.86	132.4	397.3	0.983
27°C	AM	M0	-2.35	2.53	318.3	955.0	0.774	0.70	0.16	0.8	2.4	0.294	0.39	0.14	0.1	0.2	0.590
		M3	-0.59	0.38	3.7	11.1	0.961	1.27	-0.45	6.3	19.0	0.987	0.76	-0.22	6.4	19.1	0.974
		M5	-1.04	0.96	2.0	5.9	0.973	1.14	-0.20	4.5	13.6	0.901	0.63	-0.08	1.5	4.6	0.940
	PM	M0	0.05	1.18	18.8	56.5	0.971	0.82	-0.95	32.9	98.6	0.981	0.33	-0.44	16.3	48.9	0.978
		M3	-0.38	1.59	3.3	9.8	0.986	1.06	-0.91	7.1	21.4	0.966	0.62	-0.51	5.1	15.3	0.958
		M5	-0.86	2.08	1.5	4.5	0.989	1.19	-1.09	1.9	5.7	0.977	0.65	-0.55	1.2	3.7	0.987
30°C	AM	M0	1.31	-1.51	0.2	0.5	0.971	-0.37	1.30	1.0	2.9	0.986	-0.21	0.77	0.6	1.9	0.970
		M3	0.34	-0.43	0.1	0.2	0.609	0.43	0.30	0.1	0.2	0.510	0.25	0.20	0.1	0.4	0.604
		M5	-0.15	0.45	9.7	29.2	0.934	0.88	-0.44	9.8	29.5	0.984	0.50	-0.22	9.4	28.2	0.985
	PM	M0	0.97	1.25	23.9	71.6	0.994	-0.30	-0.79	23.8	71.5	0.927	-0.19	-0.41	22.9	68.8	0.922
		M3	0.50	1.14	4.8	14.3	0.981	0.25	-0.75	5.7	17.1	0.982	0.15	-0.35	6.9	20.7	0.973
		M5	-0.02	1.63	2.2	6.5	0.987	0.65	-1.09	3.0	9.1	0.968	0.41	-0.56	3.2	9.7	0.956

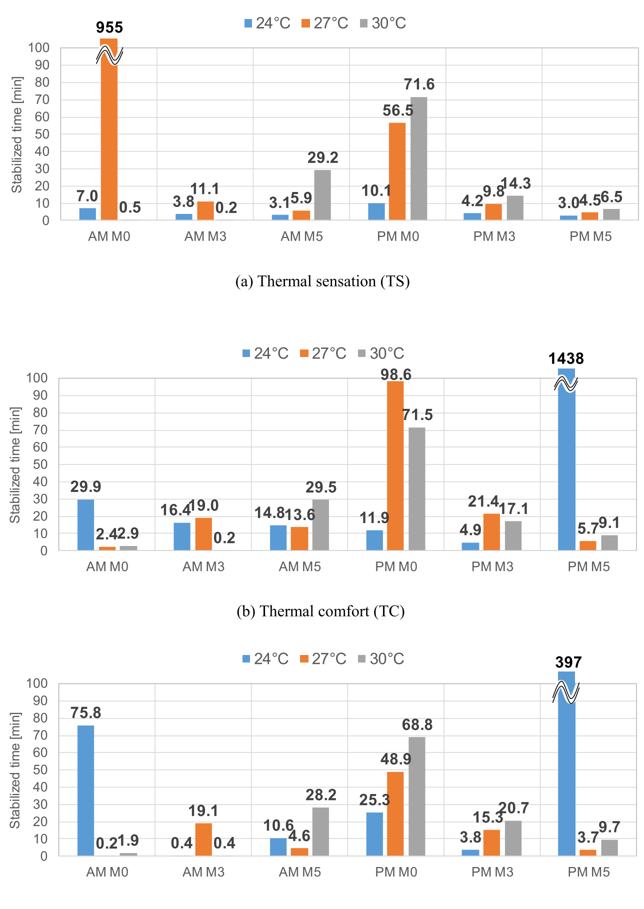


Fig. 7. Stabilized times for thermal sensation, comfort and acceptability at each indoor temperature setting and each fan speed mode.

metabolic rate at each indoor temperature setting with M3 and M5 ($p < 0.001$) except at 27 °C with M3.

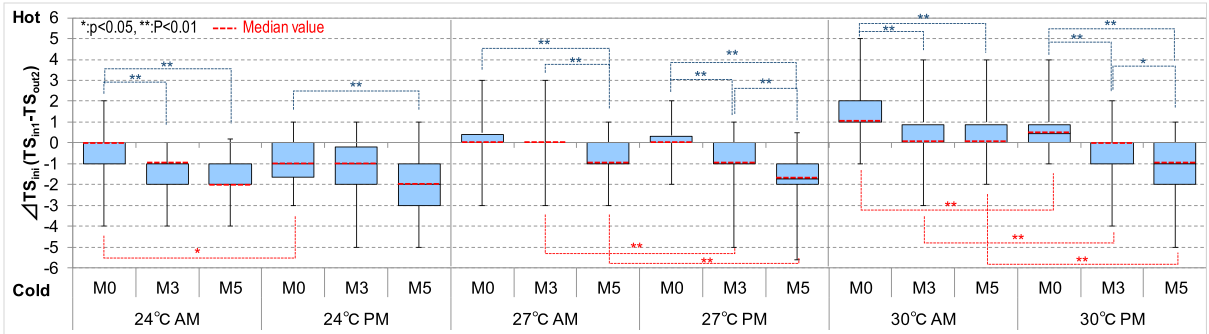
The immediate changes in TA moved to acceptable side at 27 and 30 °C with elevated air movement (Fig. 8(c)). There were statistically significant differences in TA attributed to fan speed modes between M0 and M3 ($p < 0.001$), and M0 and M5 ($p < 0.001$) in the AM sessions at 30 °C and in the PM sessions at 27 and 30 °C. The differences in TA attributed to initial metabolic rate differences were significant with M3 and M5 ($p < 0.001$). It is, thus, observed that in cases involving high initial metabolic rates, elevated air speeds caused the immediate changes in TS to move towards cool side and an improvement in TC and TA.

4. Discussion

Temperature, air movement and initial metabolic rate affected transient thermal sensation. In this study, TS reached steady-state within 15 min and TC and TA within 25 min at 27 and 30 °C with elevated air movement.

Temperature is an important factor for transient thermal sensation. When a person is exposed to temperature change, body heat balance is maintained by adjustment of skin blood flow under thermoregulatory system. Previous studies have reported the stabilized time of the mean skin temperature when subjects were exposed to temperature step change [21–23]. In these studies, subjects stayed in a chamber for thermal acclimation and calmed down their metabolic rate in these studies before they experienced thermal step change. In our study, outdoor chamber was not used for subject's acclimation. However, subjects' initial metabolic rate in the AM sessions before entering the room was calmed down as they were rested for 10 min outside the experimental room.

Liu [24] reported that it took about 15 and 20 min for mean skin temperature to reach steady-state when subjects were exposed to a 3 °C of down-step and up-step respectively. However, there has been little discussion about time to stabilize thermal sensation, thermal comfort and thermal acceptability under temperature step exposure. In our study, TS votes reached steady-state within 7 min at 24 °C with M0, as seen from Table 7. Although TC and TA votes are seen to be stabilized at



Fan Speed mode

	24°C AM	24°C PM	27°C AM	27°C PM	30°C AM	30°C PM
M0-M3	<0.001**	0.449	0.652	<0.001**	<0.001**	<0.001**
M0-M5	<0.001**	<0.001**	<0.001**	<0.001**	<0.001**	<0.001**
M3-M5	0.160	0.327	<0.001**	0.007**	0.548	0.043*

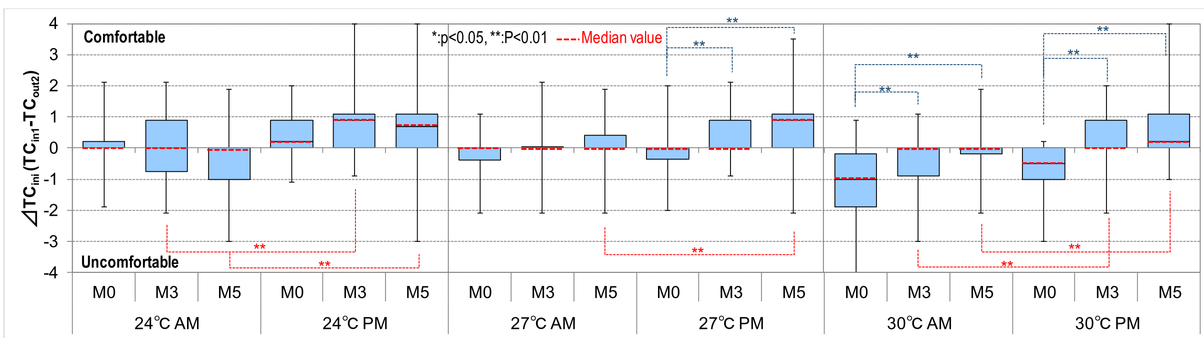
Temperature

	AM M0	AM M3	AM M5	PM M0	PM M3	PM M5
24°C-27°C	0.007**	<0.001**	<0.001**	<0.001**	0.079	0.547
24°C-30°C	<0.001**	<0.001**	<0.001**	<0.001**	<0.001**	<0.001**
27°C-30°C	<0.001**	<0.001**	<0.001**	0.005**	0.558	0.350

Initial metabolic rate

	AM-PM 24°C	AM-PM 27°C	AM-PM 30°C
M0	0.049*	1.000	<0.001**
M3	0.989	<0.001**	<0.001**
M5	0.814	<0.001**	<0.001**

(a) Thermal sensation



Fan Speed mode

	24°C AM	24°C PM	27°C AM	27°C PM	30°C AM	30°C PM
M0-M3	1.000	0.624	0.511	<0.001**	<0.001**	<0.001**
M0-M5	0.085	1.000	0.585	<0.001**	<0.001**	<0.001**
M3-M5	0.767	1.000	1.000	0.077	0.899	0.606

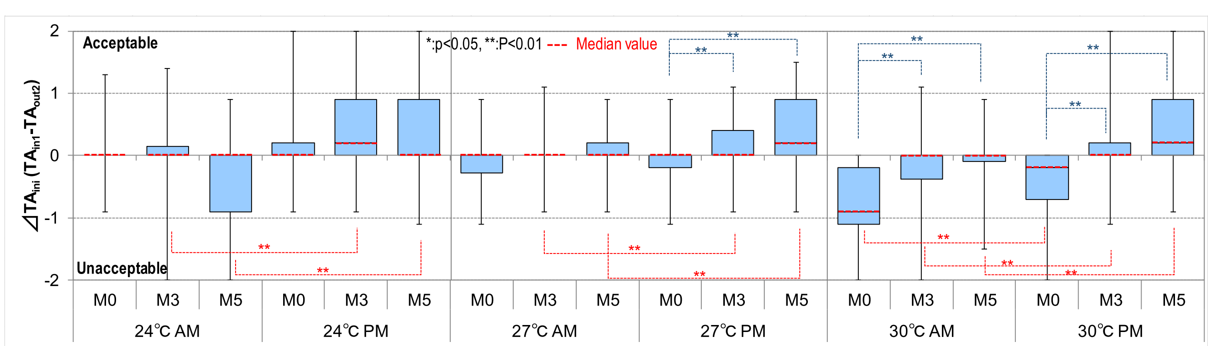
Temperature

	AM M0	AM M3	AM M5	PM M0	PM M3	PM M5
24°C-27°C	0.344	1.000	0.204	<0.001**	0.235	0.994
24°C-30°C	<0.001**	0.171	1.000	<0.001**	0.026*	1.000
27°C-30°C	<0.001**	<0.001**	0.443	0.002**	1.000	0.987

Initial metabolic rate

	AM-PM 24°C	AM-PM 27°C	AM-PM 30°C
M0	0.297	1.000	0.058
M3	<0.001**	0.277	<0.001**
M5	<0.001**	<0.001**	<0.001**

(b) Thermal comfort



Fan Speed mode

	24°C AM	24°C PM	27°C AM	27°C PM	30°C AM	30°C PM
M0-M3	1.000	0.422	0.308	<0.001**	<0.001**	<0.001**
M0-M5	0.416	1.000	0.052	<0.001**	<0.001**	<0.001**
M3-M5	0.690	0.989	1.000	0.539	0.913	0.773

Temperature

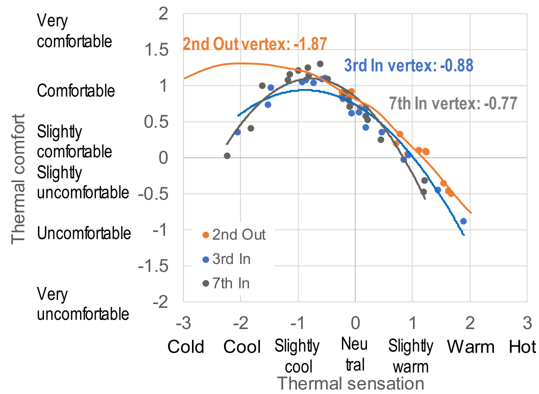
	AM M0	AM M3	AM M5	PM M0	PM M3	PM M5
24°C-27°C	0.452	1.000	0.106	<0.001**	0.982	0.730
24°C-30°C	<0.001**	0.244	0.993	<0.001**	0.109	1.000
27°C-30°C	<0.001**	0.041*	0.609	0.108	0.874	0.952

Initial metabolic rate

	AM-PM 24°C	AM-PM 27°C	AM-PM 30°C
M0	0.176	1.000	0.002**
M3	<0.001**	0.007**	<0.001**
M5	<0.001**	<0.001**	<0.001**

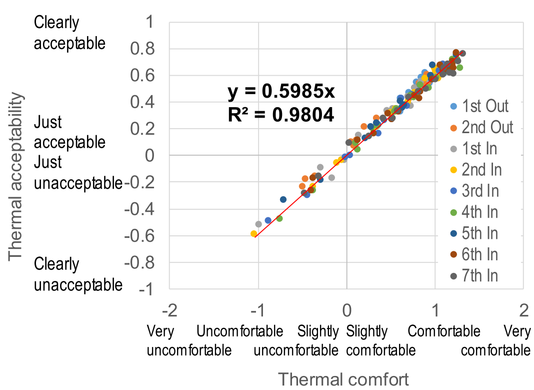
(c) Thermal acceptability

Fig. 8. Immediate changes in thermal responses between 2nd outdoor votes and 1st indoor votes after entry into the test room. Numbers in the table are p-values indicating significance of statistical difference between the respective compared scenarios.



Data	Approximate curve	R^2	Vertex
1st Outdoor	$y = -0.9778x^2 - 0.736x + 0.7785$	0.503	-0.38
2nd Outdoor	$y = -0.1376x^2 - 0.5137x + 0.7819$	0.971	-1.87
1st Indoor	$y = -0.2141x^2 - 0.3965x + 0.6877$	0.950	-0.93
2nd Indoor	$y = -0.2333x^2 - 0.4291x + 0.7062$	0.957	-0.92
3rd Indoor	$y = -0.2623x^2 - 0.4597x + 0.7368$	0.934	-0.88
4th Indoor	$y = -0.2921x^2 - 0.5034x + 0.7763$	0.892	-0.86
5th Indoor	$y = -0.3455x^2 - 0.5478x + 0.7901$	0.920	-0.79
6th Indoor	$y = -0.4024x^2 - 0.608x + 0.8467$	0.923	-0.76
7th Indoor	$y = -0.4211x^2 - 0.6485x + 0.8476$	0.912	-0.77
All	$y = -0.2755x^2 - 0.4532x + 0.7772$	0.897	-0.82

(a) Thermal sensation vs thermal comfort



Data	Approximate curve	R^2
1st Outdoor	$y = 0.5553x + 0.0682$	0.754
2nd Outdoor	$y = 0.5588x + 0.0636$	0.993
1st Indoor	$y = 0.5779x + 0.0335$	0.982
2nd Indoor	$y = 0.5952x + 0.0147$	0.995
3rd Indoor	$y = 0.5973x + 0.0032$	0.993
4th Indoor	$y = 0.5796x + 0.0012$	0.989
5th Indoor	$y = 0.5661x + 0.0339$	0.986
6th Indoor	$y = 0.5724x + 0.0115$	0.987
7th Indoor	$y = 0.5474x + 0.0232$	0.988
All	$y = 0.5985x$	0.980

(b) Thermal comfort vs thermal acceptability

Fig. 9. Relationship between thermal sensation and thermal comfort, and relationship between thermal comfort and thermal acceptability including the data from 1st outdoor votes to 7th indoor votes at each indoor temperature setting with each fan speed mode in both AM and PM sessions.

29.9 and 75.8 min respectively (Table 7), which is relatively long, TC and TA votes were almost comfortable and acceptable from 2nd outdoor to 1st indoor votes and had small variations after entry into the room, as can be seen in the AM sessions at 24 °C with M0 under an average 2 °C down-step [Figs. 5(b)-1 and Fig 5(c)-1]. Near thermal comfort, the stabilized time has little practical importance. It is observed from Table 7 that TS, TC and TA votes reached steady-state within 3 min with an average 2.4 °C up-step in the AM sessions at 30 °C with M0. The stabilized times for thermal responses were relatively shorter compared with those for the mean skin temperature. It is reported that thermal sensation changes faster than skin temperature [20,21,23]. However, temperature difference between outdoor and indoor was not constant and was a limitation in our study. Further research is required on the stabilized time for thermal response under temperature change.

It has been clearly observed in our study that air movement affects transient thermal sensation. The stabilized times of TS, TC and TA at M5 (1.87 m/s) were shorter than those at M0 (0.07 m/s) at 27 and 30 °C. Convective cooling produced by elevated air movement expedites body heat dissipation and moderates vasodilation and sweating at 27 and 30 °C.

Initial metabolic rate is another important factor for thermal sensation transients. When core temperature rises due to exposure to warm temperature and activity, body heat dissipation increases to cool the core temperature by vasodilation and sweating. In our study, significant differences in TS attributed to initial metabolic rate were found within the first 10 min at 27 and 30 °C. Goto et al. [18] also found that thermal sensation stabilized within 15–20 min with high initial metabolic rate even though ambient temperature was moderate at 21 and 26 °C with low air velocity of less than 0.1 m/s. On the other hand, our experimental conditions were warmer temperatures of 27 and 30 °C and higher air speeds from 0.94 to 1.87 m/s. Subjects sweated in the PM sessions with high initial metabolic rate at each indoor temperature setting. Skin wettedness and wet clothing caused by sweating accelerate evaporative heat loss and affect thermal sensation. The change rates in TS in the PM sessions were faster than those in the AM sessions, as shown in Fig. 6(a). In addition, the differences in TS attributed to initial metabolic rate between the AM and PM sessions were insignificant from 1st indoor votes at 27 and 30 °C with M5. On the other hand, there were significant differences in TS due to initial metabolic rate until first few minutes at 27 °C with M0 and 30 °C with M0. Hence, the effect of the initial metabolic rate on TS declined earlier at higher air speeds.

When subjects experienced sudden temperature step-down, cold sensation overshoot in TS votes was observed in the first few minutes and then TS votes returned to steady-state [20–23]. The capacity of thermoregulatory system may overload when thermoreceptors experience a sudden temperature change. Overshoot of TS votes in the AM sessions with M0 were not found at each indoor temperature setting when subjects experienced sudden temperature change in our study. This is because the temperature differences between indoor and outdoor were small, less than 4 °C at each indoor temperature setting. This could be attributed to the thermoregulatory system working well under a step change of 4 °C or less [22]. There were also no occurrences of overshoot in TC and TA votes in the AM session with M0 at each indoor temperature setting. This is consistent with previous studies that have not shown overshoot in TC and TA under a step change of less than 12 °C [23]. When subjects received air movement in the AM sessions at M3 and M5, overshoots of TS, TC and TA votes were not observed at 24 and 27 °C. However, overshoot of TS, TC and TA votes occurred initially and then returned to a steady-state in the AM sessions with 30 °C at M3 and M5. Significant differences between 1st and 7th votes were observed in the AM sessions with M3 (TS: $p = 0.001$, TC: $p < 0.001$, TA: $p = 0.037$) and M5 (TS, TC and TA: $p < 0.001$). Overshoot was observed when subjects experienced up-step temperature change at air speeds of M3 and M5. Subject felt warm at 1st indoor vote (1 min) after entering the room because their metabolic rate had increased due to walking and they were exposed to a warm temperature of 30 °C suddenly. However, their sensation was moderated in a few minutes under still conditions due to the effect of air movement cooling the skin.

The relationship between thermal sensation and thermal comfort, and the relationship between thermal comfort and thermal acceptability is examined using the data from 1st outdoor votes to 7th indoor votes for each indoor temperature setting and each fan speed mode in both the AM and PM sessions.

The relationship between thermal sensation and thermal comfort is approximated by a function of a quadratic curve whose vertex corresponding to optimal thermal comfort is slightly cool at −0.82 (Fig. 9(a)). The finding is consistent with findings of previous studies by Gong [25] and Li [26], in which tropically acclimatized people preferred thermal sensation between neutral and slightly cool in steady-state condition.

An interesting issue was whether thermal comfort changed during thermal transience. This was examined by comparing each vertex of the approximation quadratic curve for each set of votes from 1st outdoor to 7th indoor surveys. Except for the data associated with the 1st outdoor votes, there was a clear trend of the optimal thermal comfort shifting from cool (−1.87) to slightly cool (−0.77). The 1st outdoor votes showed an optimal thermal comfort associated with a relatively less cool thermal sensation. This could be due to the vote being registered before the subjects walked. The metabolic rate of each subject was different at 1st outdoor votes because some subjects took adequate rest and others walked during a break before 1st outdoor votes. On the other hand, subjects experienced similar activity from 2nd outdoor votes to 7th indoor votes. The coefficient of determination (R^2) of 1st outdoor votes was also lower than others.

Similar findings were reported in which the preferred temperature was shown to be increased as the metabolic rate decreased [15,27]. When thermoregulatory system tries to maintain heat balance between body core and ambient environment, subjects prefer cooler temperature to accelerate heat dissipation. During thermal transient phase, as the body continues to lose heat at a rate higher than that created by metabolism, as is the case when the subjects have now become sedentary, a gradual shift towards optimal thermal comfort at a less cool thermal sensation was manifested.

When preferred thermal sensation, commensurate with optimal thermal comfort based on data from 2nd outdoor to 7th indoor are fitted by exponential curve using equation (1), the approximation curve is as follows (Fig. 10).

$$y = -0.815 - 0.3875 \cdot \exp(-t/1.003) \tag{2}$$

The stabilized time of preferred thermal sensation (3τ) is 3 min. Therefore, the relationship between thermal sensation and thermal comfort follows quadratic curve even during the transient phase in the same manner as steady-state condition [25,26]. The preferred thermal sensation also changes from cool to slightly cool as the metabolic rate moderates.

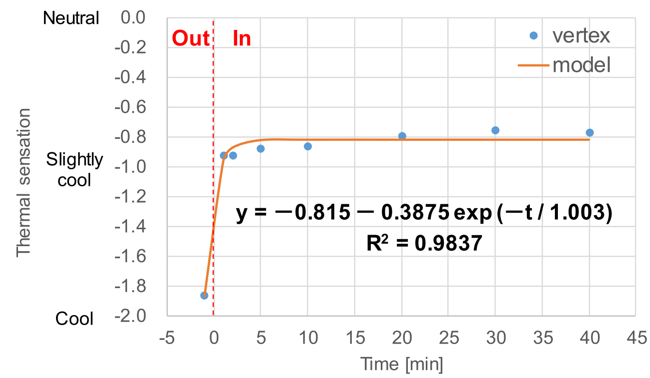


Fig. 10. Changes in preferred thermal sensation from 2nd outdoor votes to 7th indoor votes.

The relationship between thermal comfort and thermal acceptability is fitted by a linear function with high correlation, as shown in Fig. 9(b). Thermal acceptability increases as thermal comfort improves. The linear function is also calculated based on each vote from 1st outdoor to 7th indoor votes. The slope at each vote is almost the same from 0.55 to 0.60. The linear relationship between thermal comfort and thermal acceptability is found for both transient and steady-state conditions.

This study has examined the effects of temperature, air movement and initial metabolic rate on transient thermal sensation in warm environments. There are, however, some limitations of our study. The subjects were seated only under the ceiling fans. However, occupants may stay at locations other than under the ceiling fans in an actual building. Transient thermal sensation at other locations needs to be investigated. In addition, we only investigate transient thermal sensation when subjects enter from outdoor to an air-conditioned room. When subjects enter from a cooler air-conditioned room to a warm environment, transient thermal sensation may be different from our results.

5. Conclusions

In this study, the effects of temperature, air movement and initial metabolic rate on transient thermal sensation were examined in a classroom setting.

Transient votes of thermal sensation, thermal comfort and thermal acceptability were analysed. Temperature and air movement have a large influence on thermal sensation during thermal transient phase. Adverse effects of thermal sensation in the first few minutes were alleviated earlier with elevated air movement. Thermal comfort and acceptability were affected by temperature at low air speeds of 0.07 m/s, and by air movement at warmer temperatures of 27 and 30 °C. The adverse effect of initial metabolic rate on thermal sensation was moderated within 10 min at each indoor temperature setting with elevated air speeds from 0.94 to 1.87 m/s. The initial metabolic rate also affected thermal comfort and acceptability within 10 min at 27 and 30 °C with low air speeds of 0.07 m/s.

Thermal responses stabilized early at higher air speeds. Thermal sensation, thermal comfort and thermal acceptability reached steady-state within 15 and 25 min respectively at 27 and 30 °C with elevated air movement between 0.07 and 1.87 m/s. Immediate change in TS was cooler and those in TC and TA got better with higher initial metabolic rate and air speeds from 0.94 to 1.87 m/s. In cases involving high initial metabolic rate at 30 °C, the changes in TC and TA with elevated air movement from 0.07 to 1.87 m/s were towards improved TC and TA.

As reported in studies involving steady-state condition, thermal comfort was maximized when tropically acclimatized people felt slightly cool at −0.82 even during the transient phase. The preferred thermal sensation moved from cool (−1.87) to slightly cool (−0.77) as the metabolic rate decreased. The relationship between thermal comfort and acceptability followed a linear function during the transient phase. The effects of air movement on thermal sensation and PAQ in warm environments in steady-state conditions will be analysed in the future.

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