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Transient human thermophysiological and comfort responses indoors after simulated summer commutes

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ABSTRACT

The current study investigates the transient human physiological and comfort responses during sedentary activity following a period of elevated activity in a hot condition. Such metabolic and thermal down-steps are common in buildings as occupants arrive after commuting in summer. It creates a serious problem for thermostatic control, since arriving occupants find their transition uncomfortably warm at temperatures that resident occupants find comfortable. Fifty-nine participants (29 men, 30 women) dressed in 0.6 clo were tested while sedentary for 60 min in 26 °C, after having been exposed to 30 °C for 15 min, during which they performed activities metabolically simulating commuting: sitting (SE - 1.2 met), or doing three levels of stair-step exercises: low (LEx- 2.2 met), medium (MEx - 3.0 met), and high (HEx - 4.4 met). Subjective comfort and physiological responses (metabolic rate, skin temperature, skin blood flow rate, heart rate, core temperature, and skin wettedness) were collected. Results show that sedentary conditions at 26 °C became comfortable and acceptable within 2 min, but thermal sensation required much longer to change from 'warm' or 'hot' to 'neutral': 0, 8, 17, 30 min after SE, LEx, MEx, HEx respectively. Skin wettedness and core temperature did not recover within the 60 min. The delays are mainly due to body heat stored during the exercise. A room temperature of 26 °C may not provide sufficient cooling after summer commuting. Localized convective cooling of transitional spaces and work areas by ceiling or desk fans represent a way to enhance comfort recovery.

1. Introduction

Although thermal comfort research and standards assume steady metabolic rates, they are naturally transient in people's daily life. For example, occupants usually arrive at offices, schools, railway/subway stations, museums or other types of indoor environments by a variety of means (e.g. walking, cycling, or driving), almost all of which involve higher levels of physical exertion than the ultimate state of sedentary office work. Metabolic rate is typically elevated outdoors and drops after entering the building. Such metabolic down-steps, accompanied by downward outdoor-indoor temperature transients in warm weather, influencing occupants' thermal comfort after entering indoor spaces. However, current thermal comfort standards, models, and design guidance have mainly focused on the condition of lengthy sedentary office activity [1,2]. When occupants transition from high to low metabolic rates, the comfort zones for sedentary activity might be perceived as too warm for many minutes during the cool-down period. The occupants may complain about the space being too warm or stuffy (a correlate of warmth sensation). Building operators respond to such complaints by changing zone setpoints, often permanently, rendering the entire space cooler thereafter than is necessary for sedentary work. This could contribute to the widely observed problem of summer overcooling [3] and the energy use of the building [4].

Many studies have addressed temperature step-changes at a constant sedentary metabolic rate [5–9]. They generally found that under sudden temperature transients, the human psychological response is significantly affected by the previous thermal conditions experienced, and that thermal sensation and comfort often quickly anticipate the new condition, ahead of the physiological responses that take more time to transition [5]. This phenomenon, sometimes called thermal sensation overshoot, is more likely to occur when people move from warm/hot temperatures to neutral/cool temperatures, such as moving from summer outdoors into air-conditioned buildings. Based on these studies, recommendations have been made for the environmental

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List of symbols and abbreviations

A_{Du}	Du Bois body surface area
AMA	Air movement acceptability
AMP	Air movement preference
EE	Energetic equivalent
Ex	Exercise
HEx	High exercise intensity, simulating cycling
HR	Heart rate
MET	Metabolic rate
MEx	Medium exercise intensity, simulating fast walking
LEx	Low (light) exercise intensity, simulating slowly walking
P_a	Ambient vapor pressure
P_m	Vapor pressure at the skin surface
post-Ex	Post-exercise
P_{ssk}	Saturated vapor pressure at skin temperature
pre-Ex	Pre-exercise
RM ANOVA	One-way Analysis of Variance repeated measures
RPE	Borg Rating of Perceived Exertion (RPE) Scale
RQ	Respiratory quotient
SBF	Skin blood flow
SE	Sedentary, simulating driving
SD	Standard deviation
TA	Thermal acceptability
T_b	Body temperature
TC	Thermal comfort
T_{cr}	Core temperature
TP	Thermal preference
TS	Thermal sensation
T_{sk}	Skin temperature
V_{CO2}	Carbon dioxide generation rate
V_{O2}	Oxygen consumption rate
WET	Skin wettedness

design of transitional spaces, such as allowable temperature differences between transitional spaces and building interior spaces that should not be higher than 3 °C to avoid burden on human thermoregulatory system [10,11].

However, it is doubtful that results from studies that dealing only with temperature transients will apply if metabolic rate also changes. During steady-state exercise, elevated metabolic rates increase human core temperature, skin temperature, and sweat rates [12], resulting in different thermal neutral temperature from sedentary [13,14], as well as preferred skin temperature and skin wettedness [15,16]. Using four subjects exercising at different intensities in 10, 20 and 30 °C Gagge et al. [17] found that during metabolic rate transients, comfort and thermal sensation is primarily related to body temperature, while in steady-state thermal responses are dominated by skin temperature and skin wettedness. Therefore, different underlying mechanism may exist for steady-state and transients. Goto et al. [18] investigated the effect of metabolic transients on human thermal responses at 26 °C and 21 °C, finding that metabolic rate step-changes (up-steps and down-steps) significantly affected thermal sensation immediately after the onset and cessation of exercise. They applied weights to preceding metabolic levels in a model predicting thermal sensation changes after transients. However, the temperature in their study remained the same so that the combined effect of temperature and metabolic rate transients was not explored. Recently, several other studies [19–24] have examined thermal transients induced by both temperature and metabolic rate, but they focused on effective ways to alleviate thermal discomfort induced by exercise in the heat, rather than investigating the underlying mechanism of human thermal responses under such conditions.

In sports science, it has been shown that a large amount of heat can be stored during exercise. This is mainly due to the lag of evaporative heat loss in the early stage of exercise [25], resulting in elevated core and muscle temperatures that persist throughout the exercise and even an hour after prolonged exercise [26]. Post-exercise thermoregulation studies show that the stored heat requires a longer time to dissipate because of marked suppression in heat loss responses, such as skin surface blood flow and sweat rate right after cessation of exercise [27]. This would reduce the convective heat transfer between muscle and blood and between blood and the body core region. In addition, the convective and evaporative heat losses from the skin are also reduced because the air velocity induced by exercise reduces to zero after the cessation of the exercise. Therefore, prolonged core temperature recovery time has been observed, although the mechanism of the compromised ability of heat dissipation has not been fully understood and mainly attributed to nonthermal factors. These findings have important implications for understanding thermal comfort after exercise, but they are not directly applicable to typical building environments, because they do not obtain subjects' thermal and comfort sensations, and they are mainly done at high activity levels with subjects dressed in shorts.

Overall, to-date there has been little investigation of the effect of previous activity levels on subsequent human thermal responses in buildings or vehicles. For the design and operation of office buildings, it would be very helpful to be able to know how the thermal experience (physiological and subjective) induced by commuting outdoors in the heat affects human physiological and thermal comfort responses after a transition to cooler (near-neutral) indoor environments and to sedentary activities. Therefore, the objective of this study is to investigate how the persistence of heat or sweat from previous metabolic exertion affects subjects' response to the thermal environment during subsequent lower activity levels.

2. Methods

The experiments were conducted at the climate-controlled chamber at the Xi'an University of Architecture and Technology in August 2017 and June to July 2018. The outdoor temperatures during this period were generally warm, ranging from low at 22–26 °C to high at 32–39 °C.

2.1. Subjects and clothes

Fifty-nine healthy Chinese college-age students (29 men, 30 women) participated in all 4 experiments as human subjects. Their demographic information is summarized in Table 1. They were dressed in the Kansas State University uniform (0.6 clo) that has been a de-facto standard in many comfort studies [1], provided by the research group. It is comprised of a cotton long-sleeve shirt, long cotton pants, shoes, socks, and the subject's own underwear. The study was approved by the Xi'an University of Architecture and Technology Committee for the Protection of Human Subjects.

2.2. Experimental conditions

The tests were conducted in two climate chambers connected by a

Table 1
Subjects' demographic information.

	Sample size	Age	Height (cm)	Weight (kg)	BMI[a] (kg/m^2)
Men	29	23.3 ± 3[b]	175.4 ± 5	65.8 ± 6	21.4 ± 2
Women	30	22.4 ± 3	162.5 ± 7	52.8 ± 6	19.9 ± 2
all	59	22.9 ± 3	168.9 ± 9	59.2 ± 9	20.7 ± 2

[a] Body Mass Index (BMI) = Mass (kg)/Height $(m)^2$.
[b] Standard deviation.

door (Fig. 1a). One test chamber (Room B, measuring 3.0 m × 2.1 m × 2.4 m) was controlled to simulate the summer outdoor condition (30 °C, 50% RH); the other (Room A, Fig. 1a, measuring 4.5 m × 3.9 m × 2.7 m) was used to simulate a typical office environment (26 °C, 50% RH). Both chambers are located inside a building, isolating from outdoor weather. They are also heavily insulated (100 mm polyurethane board) to ensure stable indoor thermal environment control. The chambers control temperature to an accuracy of ± 0.2 °C, and RH ± 5%. During the tests, room air speed was controlled lower than 0.1 m/s, and mean radiant temperature the same as room air temperature during all test conditions.

The experiment was separated into three phases (Table 2): (1) Pre-exercise phase (pre-Ex), during which subjects stayed in Room A for 30 min; (2) exercise phase (Ex) in Room B, in which subjects were asked to perform stepping activities on a 14 cm height bench for 15 min. There were three exercise levels: (1) walking slowly, light exercise intensity (LEx), simulated by stepping at 20 steps/min; (2) walking fast, medium exercise intensity (MEx), 30 steps/min; and cycling, high exercise intensity (HEx), 40 steps/min. In addition, a fourth condition had the subjects remaining sedentary (SE) in Room B, to simulate driving or taking public transit in the heat; this condition also serves as the control condition since it involved no exercise. (3) Post-exercise recovery phase in Room A where subjects remained sedentary for an hour.

2.3. Measurements

2.3.1. Environmental parameter measurements

In addition to the sensors in the chamber control system, additional measurements were made: air temperature/relative humidity (TD/TR-72ui, T&D Corp., Nagano-ken, Japan, temperature accuracy ± 0.3 °C, RH accuracy ± 5%), globe temperature (HQZY-1, TianJianhuayi Co., Ltd, Beijing, China, accuracy ± 0.3 °C), and air speed (WFWZY-1, TianJianhuayi Co., Ltd, Beijing, China, accuracy ± 0.05 m/s), to make sure that the test chambers were controlled according to the experimental design. The sensors are installed in the middle of Room A (pre- and post-exercise), and near a corner of Room B (exercise). The exact places are shown in Fig. 1a.

2.3.2. Physiological measurements

Two sets of experiments were conducted. The first, performed at the same time of the subjective voting tests, measured heart rate (HR), skin temperature (T_{sk}) (n = 28 out of the 59 subjects) and skin wettedness (WET) (n = 19 out of the 59 subjects). The second set measured the physiological responses for a subset of the initial subjects on separate occasions after the initial tests, including metabolic rate (MET) (n = 9), core temperature (T_{cr}) (n = 9), and skin blood flow (SBF) (n = 3). All physiological parameters were sampled continuously every 1 min. The physiology measurement sensors are shown in Fig. 1.

T_{sk} was continuously measured using small wireless temperature sensors (Fig. 1d, PyroButton-L, Opulus Ltd, PA, USA). The measuring points were arranged on the left upper chest, left forearm, middle of left-thigh and middle of the left shin. Mean T_{sk} was calculated as an area-weighted average of measurements using the following equation, adapted from NL Ramanthan [28].

$$mT_{sk} = 0.3 \times T_{arm} + 0.3 \times T_{chest} + 0.2 \times T_{thigh} + 0.2 \times T_{shin} \quad (1)$$

WET was calculated using the following equation, adapted from Kerslake [29].

$$WET = (P_m - P_a) / (P_{ssk} - P_a) \quad (2)$$

where. P_m = vapor pressure at skin surface. P_a = ambient vapor pressure. P_{ssk} = saturated vapor pressure at skin temperature.

P_a, is considered to be constant around the body and is based on the average temperature and humidity of the surrounding air. P_m, is based on the measurement of the temperature and relative humidity in the space between the skin and clothing. P_{ssk} is calculated from measurements of the skin temperature using eq. (1). The temperature and relative humidity in the space between the skin and clothing was continuously measured by using small wireless temperature and relative humidity sensors (Fig. 1e, Hygrochron, EDS, USA). The total accuracy is ± 5% RH in the range 0–100% RH with a time constant of 30 s. In order to meet the measurement requirements, sensors were housed inside a short length of plastic tubing. When taped to the body, the sensors were positioned less 3 mm above the skin surface and exposed through a lateral opening in the tubing, enabling the measurements of temperature and relative humidity above the skin surface.

The measuring points were arranged on the same points as the skin temperature measurements: chest, forearm, thigh, and shin. Mean WET was calculated as an area-weighted average of measurements using the same weightings as the mT_{sk} [30].

$$WET = 0.3 \times w_{arm} + 0.3 \times w_{chest} + 0.2 \times w_{thigh} + 0.2 \times w_{shin} \quad (3)$$

MET was measured using indirect calorimetry (Fig. 1b). Human oxygen consumption rate (V_{O2}) and carbon dioxide generation rate (V_{CO2}) was monitored from −10 min to 75 min (15 min exercise + 60 min resting) continuously by a wearable metabolic measurement system (COSMED K5, COSMED S.r.l., Italy). The K5 gas sensors, flow rate, and pressure sensors were calibrated before each testing. A face mask was used to collect expired gas from the subjects, and the captured gas was analyzed in a micro-dynamic mixing chamber to obtain: V_{O2}, V_{CO2}, ventilation, and respiratory exchange ratio. The metabolic rate was then determined by the measured V_{O2}, V_{CO2}, respiratory quotient (RQ), and body surface area (A_{Du}) according to equations (4)–(7) provided by ISO 8996 [31], as follows:

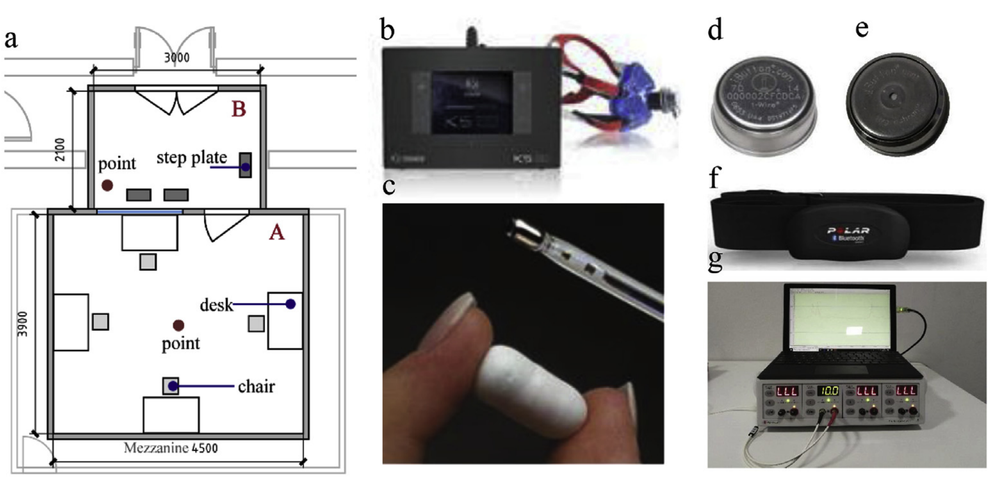

Fig. 1. (a) Experimental set-up, (b) Cosmed K5 to measure metabolic rate, (c) Ingestible telemetry pill for core temperature measurement, (d) iButton for skin temperature measurement, (e) iButtion for skin wettedness measurement, (f) Polar strap for heart rate monitoring, (g) Laser Doppler system for skin blood flow monitoring.

Table 2
Experimental conditions, durations, and activity levels.

Phase	Time (min)	Location	T (°C)	RH (%)	Metabolic rate (met)	Activity
pre-Ex	−30–0	Room A	26	50	1.2	Sedentary
SE (control)	0–15	Room B	30	50	1.2	Sedentary
LEx					2.2	Stepping, 20 steps/min
MEx					3.0	Stepping, 30 steps/min
HEx					4.4	Stepping, 40 steps/min
post-Ex	15–75	Room A	26	50	1.2	Sedentary

$$RQ = \frac{Vco_2}{Vo_2} \tag{4}$$

$$EE = 5.88 \times (0.23RQ + 0.77) \tag{5}$$

$$M = EE \times Vo_2 \times \frac{1}{A_{Du}} \tag{6}$$

$$A_{Du} = 0.202 \times W_b^{0.425} \times H_b^{0.725} \tag{7}$$

RQ is the respiratory quotient;EE is the energetic equivalent, in watt-hour per liter of oxygen (W h/l O_2);M is the metabolic rate, in watts per square meter (W/m^2); A_{Du} is the body surface area, in square meters (m^2), given by the Du Bois formula. W_b is the weight (kg), H_b is the height (m).

T_{cr} was measured using telemetry pills (Fig. 1c, accuracy ± 0.1 °C; CorTemp®, HQ Inc, Florida, USA) in four tests, for four metabolic levels. Subjects ingested pills with warm water (36.7 °C) 2 h before the test. Data were transmitted from the telemetry pill to a receiver attached on the right back hip of the subjects. Body temperature (T_b) was calculated based on measured T_{sk} and T_{cr}. T_{sk} and T_{cr} were weighted by 0.2 and 0.8 respectively, based on the equation proposed by Gagge et al. [13].

$$T_b = 0.8 \times T_{cr} + 0.2 \times T_{sk} \tag{8}$$

HR was continuously monitored by a Polar H10 (Fig. 1f, Polar Electro Oy, Kempele, Finland) by connecting wirelessly to a cell phone. SBF was measured by a PeriFlux System 5000 with a probe attached on the left forearm of the subject (Fig. 1g).

2.4. Subjective survey questions

Paper-based surveys were administrated during the exercise in Room A, while computer-based surveys were administered both before and after the exercise in Room B when subjects were sedentary. The surveys appeared at predefined intervals, to obtain point-in-time subjective responses on their thermal sensation (TS), thermal comfort (TC), thermal acceptability (TA), air movement acceptability (AMA), thermal preference (TP) (an example shown in Fig. 2, the full survey is shown in Fig. A1). The TS scale is continuous, and its units are: −4 very cold, −3 cold, −2 cool, −1 slightly cool, 0 neutral, 1 slightly warm, 2 warm, 3 hot, 4 very hot. TC, TA, and AMA were measured on a ten-point scale with a break, in which the positive values (0.01 'just acceptable' to 4 'clearly acceptable') represent satisfaction and the negative values (−0.01 'just unacceptable' to −4 'clearly unacceptable') represent dissatisfied. Three-point scales are used for thermal preference (−1 want cooler, 0 no change, 1 want warmer) and air movement preference (AMP) (−1 want less, 0 no change, 1 want more). The survey schedule is presented in Fig. 3. In addition to the regular thermal comfort questions, the subjects were asked after each exercise level to vote their perceived physical exertion on the Borg Rating of Perceived Exertion (RPE) Scale [32] (Fig. A2).

2.5. Experimental procedure

Prior to the main experiments, pilot tests on 4 subjects were conducted to validate the feasibility of the experimental design. After the test procedure was confirmed, 59 subjects were recruited for the full-scale tests. Subjects arrived at the test chamber in groups of 4 for each test. They were asked to avoid intensive exercise or consume alcohol or caffeine-containing drinks for the day before the test. Fig. 3 shows the test procedure. The subjects were asked to arrive at least 10 min before the test to avoid entering the chamber with an elevated metabolic rate. Before entering the chamber, subjects changed into test uniforms and secured the temperature, humidity sensors and HR belt to their bodies. The three phases of the test procedure were: pre-exercise, exercise, and post-exercise, as described in the experimental condition section. The subjects in each experiment were first sedentary in Room A at neutral temperature of 26 °C, 50% RH for 30 min to simulate the exposure to a neutral condition in their homes, after which they entered the second climate chamber 30 °C, 50% RH (Room B) and exercised for 15 min. They went through these Room B sequences (SE, LEx, MEx, and HEx) in

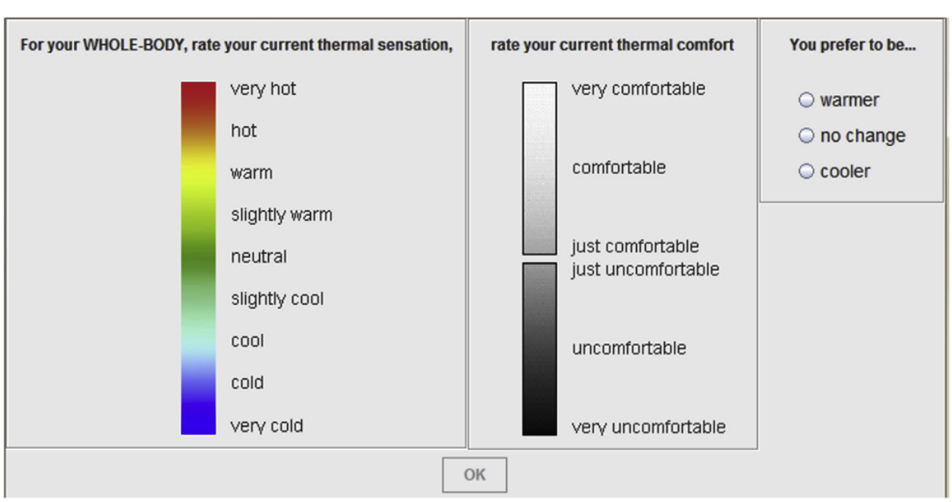

Fig. 2. Sample survey rating scales used in the experiment.

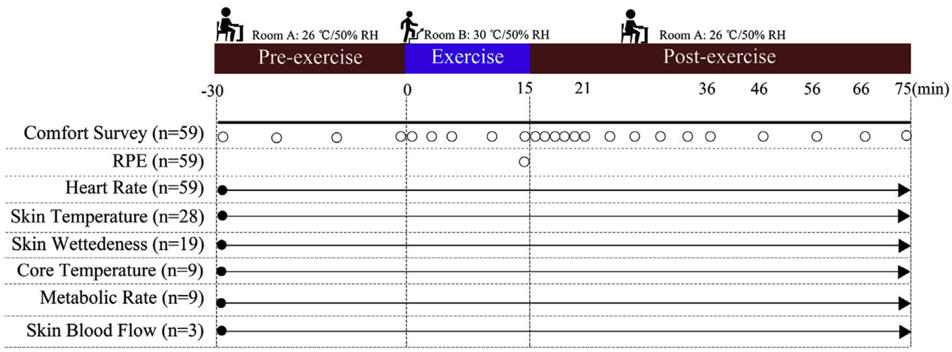

Fig. 3. Experimental procedure.

random order to simulate the four commute modes. At the end of this period, they returned to Room A, and remained sedentary for 60 min until the experiment ended, to simulate the office environment. Survey questionnaires were administrated every 10 min during the first 30 min exposure before exercise, at 0, 3, 5, 10 and 15 min during the exercise (only TS, TA were asked to save time), every 1 min after the exercise for 6 times, then every 3 min from 21 to 36 min, and then every 10 min till the end of the test (Fig. 3).

2.6. Statistical analyses

The observed physiological and subjective responses for each individual were averaged and only mean values plus standard deviations (SD) were reported in the paper. Statistical analysis was performed using Graphpad Prism 6 for Windows (GraphPad Software, San Diego, California US). The experiment was treated as a repeated measures design. The stabilized time was obtained by running one-way Analysis of Variance with repeated measures (RM ANOVA) with post-hoc analysis (Paired T-test), using exposure time as the factor. Comparisons between different activity levels (SE, LEx, MEx, and HEx) were made by RM ANOVA at a specific time point, using Activity level as the factor. Significance was accepted at 0.05.

3. Results

3.1. Physical environment measurements

As shown in Table 3, the physical conditions of the experiments were accurately controlled as planned.

3.2. Physiological responses

Fig. 4a shows the average metabolic rate as observed during the experiments. Results show that the method of simulating different activity intensities by different stepping speeds is effective. During the exercise period, the steady state MET were 1.2 met, 2.2 met, 3.0 met and 4.4 met correspond to SE, LEx, MEx, and HEx respectively, significantly higher over sedentary control condition SE ($p < 0.05$) and sedentary pre-Ex, which also served as the baseline in the data analysis (MET = 1.2, $p < 0.05$).

The MET values responded to the on and off of the exercise quickly. In all but the SE condition, MET increased rapidly at the start of exercise, and reached a stable value in 2–5 min. In the post-Ex sedentary condition, MET also recovered rapidly, reaching pre-Ex values within 5 min, and remained constant thereafter. The metabolic rate at SE floated slightly upward before and after the transients due to the moving of subjects from Room A to Room B, and remained constant at 1.2 met for the rest of the 15 min exercise period.

Fig. 4b shows the average HR changes. The change profiles are very similar to the MET change profiles in the way that they responded to the onset and cessation of the exercise within a few minutes. The difference is that during the exercise, unlike MET which reached stable values, HR kept increasing. After the 30 min pre-Ex exposure, HR was 80 ± 1.6 beats/min. Following the start of the exercise, the abrupt increases in HR happened in the first 2 or 3 min for LEx, MEx, and HEx. Then the HR continuously elevated compared to the pre-Ex baseline ($p < 0.05$). HR did not reach a steady state, especially at the higher activity levels (3.0 met - MEx and 4.4 met - HEx). HR was 89, 100, 114, and 132 beats/min at the end of the 15 min transient period for SE, LEx, MEx, and HEx, respectively. During the post-exercise phase, like MET, HR decreased immediately and returned to a steady state at the pre-exercise level in approximately 5 min.

The skin, core, body temperatures and skin wettedness show similar trends (Figs. 5–6) that are different from MET and HR changes. During the exercise, they all increased continuously and did not reach a stable condition. Some of the increases had a few minutes delay. After the exercise, they took much longer time to reach stable values, in some cases not reaching stability.

Fig. 5a shows the average T_{sk} (n = 28). Baseline T_{sk} at 26 °C ambient temperature was similar for all tests, at a steady-state around 34 °C. T_{sk} started to rise immediately after subjects entered Room B at 30 °C and started the exercise phase, even in the 1.2 met SE condition in which there was no metabolic increase, indicating a significant effect of ambient temperature on T_{sk}. At the end of the exercise period, T_{sk} was 34.3 °C, 34.4 °C, 34.5 °C and 34.8 °C respectively, about 0.3–0.8 °C higher than the baseline T_{sk} ($p < 0.05$). After the highest level of exercise (HEx, 4.4 met), the skin temperature continued to increase for about 2 min before it started to decrease. For the other exercise intensities, skin temperature started to drop right after the exercise stopped. Unlike MET and HR, T_{sk} decreased slowly, decreased exponentially before stabilizing at a new level slightly higher than 34 °C within 3 min for 1.2 met, 7 min for 2.2 met, 10 min for 3.0 met and 30 min for 4.4 met.

T_{cr} reached a steady-state at 37.3 °C after the 30 min pre-exercise exposure (Fig. 5b). Throughout the entire experiment at 1.2 met SE, T_{cr} decreased slightly but continuously from 37.4 °C from 37.3 °C. For LEx, MEx, and HEx, unlike T_{sk} that changed immediately after the exercise started, T_{cr} began to change only 5 min after the onset of the exercises, rising continuously to 37.5 °C, 37.6 °C and 37.6 °C, significantly

Table 3
Experimental conditions and measured thermal environmental values.

	Room A		Room B	
	Planned	Measured	Planned	Measured
Ta (°C)	26	25.9 ± 0.7[a]	30	30.1 ± 1.2
RH (%)	50	48.3 ± 2.1	50	45.5 ± 3.8
V (m/s)	< 0.1	0.02 ± 0.04	< 0.1	0.12 ± 0.08
MRT (°C)	26	26.1 ± 0.6	30	29.9 ± 0.7

[a] Standard deviation.

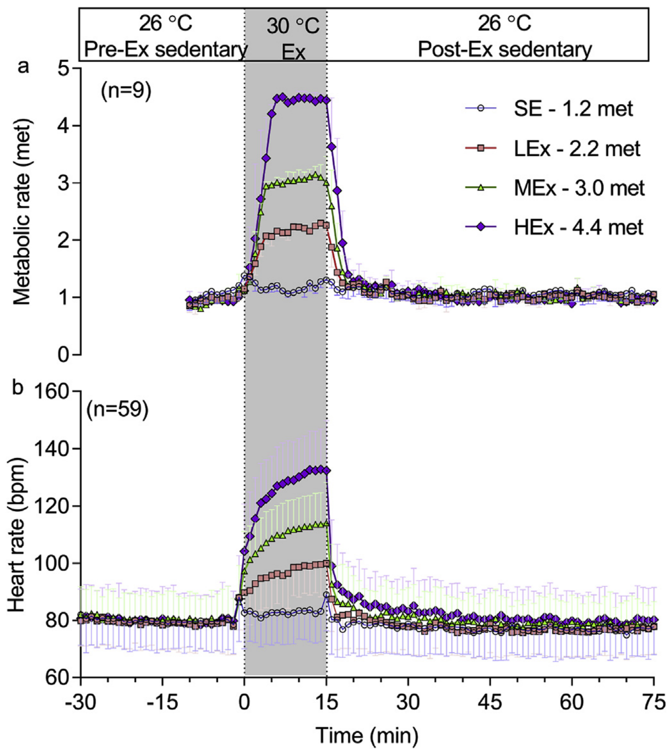

Fig. 4. Measured mean (a) metabolic rate (MET) (n = 9) and (b) heart rate (HR) (n = 59). Error bars show SD.

elevated above the baseline ($p < 0.05$). After the exercise, T_{cr} continued to increase for about 5 min for LEx and MEx before decreasing. HEx started to decrease right after the exercise stopped. However, all core temperatures remained elevated throughout the 60 min recovery period.

As shown by Eq. (8), T_b is mainly affected by the core temperature. Therefore, it shows a similar trend as T_{cr} (Fig. 5c). T_b was around 37 °C for all test conditions at the end of the pre-exercise phase. After 15 min exercise at LEx, MEx, and HEx, T_b was elevated to 37.2, 37.4 and 37.5 °C respectively, and remained elevated for an hour throughout the entire experiment. Since T_b represents heat storage in the body, it can be estimated that the higher the activity level, the higher the heat storage in the human body.

Fig. 6 shows the temporal change in the mean WET for all test conditions. The mean WET was 0.2 after 30 min of exposure in the baseline. It increased immediately after the start of the exercise in 30 °C, and continuously increased 0.07, 0.28, 0.37, and 0.46 for SE, LEx, MEx, and HEx during the 15 min exercise without reaching stable conditions. After the exercise, WET continued to increase for about another 2 min for the HEx test condition before decreasing. During the post-exercise period, WET went back to the baseline level for the SE after 15 min, but continued to be at elevated levels for the full hour in the 2.2, 3.0, and 4.4 met tests.

Fig. 7 shows the result of skin blood flow (SBF) change of the subjects for all test conditions. The SBF stabilized around 9.0 perfusion units (PU) for the pre-exercise baseline condition (Fig. 7). During the 15 min exercise and temperature transient period, for SE, the 15 min exposure to the 30 °C ambient temperature only increased SBF slightly to around 10 PU. However, the increase in MET at LEx, MEx, and HEx significantly elevated SBF, reaching 18, 26 and 86 PU in the 2.2, 3.0 and 4.4 met exercise periods. They reached a stable level quickly within 2 min except for the HEx (4.4 met) test. For HEx, the SBF kept increasing, a pattern similar to HR and other skin temperature changes. During the post-exercise period, SBF quickly returned to baseline levels for LEx (1 min) and MEx (3min). 8 min was required for SBF return to

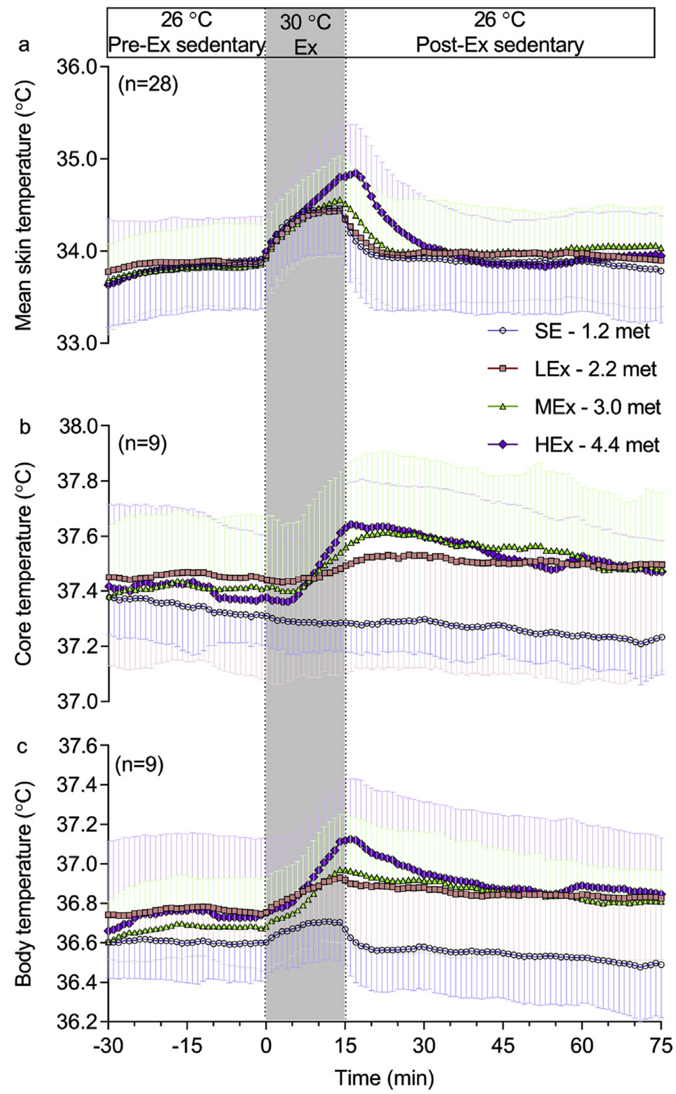

Fig. 5. Measured means (a) mean skin temperature (n = 28) (b) core temperature (n = 9) (c) body temperature (n = 9). Error bars show SD.

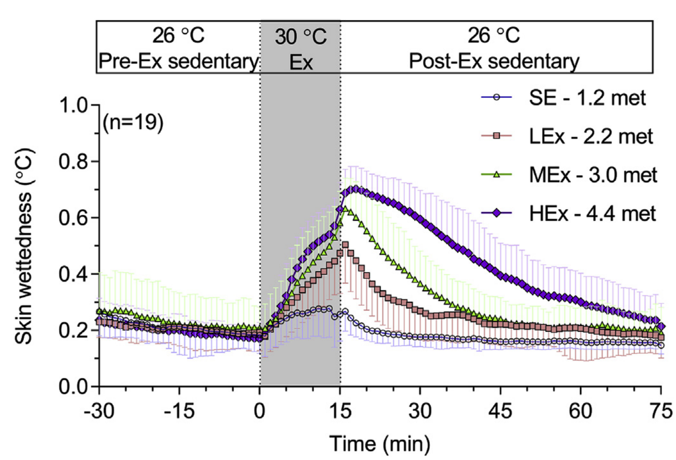

Fig. 6. Measured mean and SD skin wettedness (WET). Error bars show SD.

baseline for HEx, longer than the HR but shorter than the skin temperature recovery speeds. In general, similar to MET and HR, SBF responded to the exercise and temperature step changes quickly.

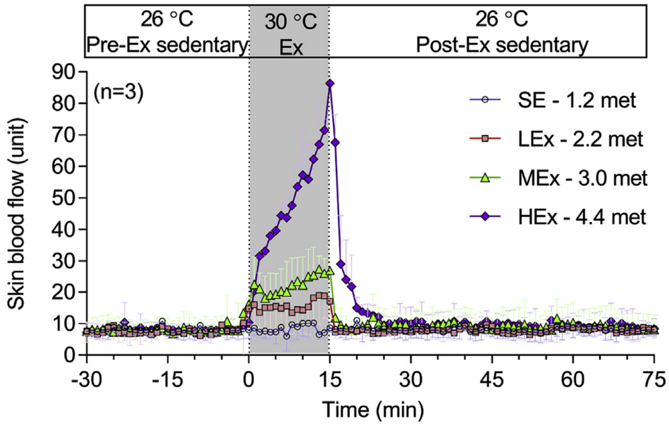

Fig. 7. Measured skin surface blood flow (SBF). Error bars show SD.

3.3. Subjective responses

Fig. 8a presents the TS for all test conditions. During the baseline exposure, mean TS stabilized at 0.3, between neutral and slightly warm. The first group of TS votes after entering Room B were obtained before the exercise started (time 0 in Fig. 8a). Therefore, the TS changes were caused only by the step-change in ambient temperature. The change from 26 °C (Room A) to 30 °C (Room B) caused TS to increase about 1.3 scale unit, from close to neutral to a value between slightly warm and warm. During the 15 min exercises in the 30 °C environment, sensations kept increasing and did not reach stable values. After the 15 min exposure, for SE, LEx, MEx and HEx, TS increased another 0.4, 1.0, 1.6 and 1.7 sensation scale units to reach 1.7 (warm), 2.2 (warm), 2.8 (hot) and 3.0 (hot) scale units respectively, significantly elevated from the baseline (0.3) ($p < 0.05$). Post-exercise, TS showed an extreme drop at the moment the subjects returned to Room A (26 °C). For SE, there was an initial over-shoot in the thermal sensation drop (cooler than neutral), then it quickly reached a stable neutral condition. For LEx, it took about 8 min to reach 0.5 scale unit and it took about 30 min to reach the level as same as baseline. For the MEx and HEx, it took about 17 min and 30min for TS to reach 0.5 scale unit, and about 40 min and 50 min to reach the baseline TS level. The recovery speeds were longer than the skin temperature recovery speeds but shorter than the core temperature recovery speeds.

Fig. 8b shows the TC votes for each test conditions, ranging from “Very uncomfortable” (−4) to “Very comfortable” (4). The subjects felt thermally comfortable during the 30 min exposure in the pre-Ex neutral condition. The profiles of the TC votes after entering Room B almost mirror the TS votes in the opposite direction. TC was just uncomfortable (the TC valued to zero) right after subjects entered into Room B before the exercise started, then decreased significantly at the end of the exercise. TC votes were on the uncomfortable side of the scale (below zero) in all conditions. However, from the beginning of the post-Ex period directly after the subject re-entered Room A, they returned to “comfortable” for the SE and LEx conditions and were below “uncomfortable” for MEx and HEx. TC increased rapidly in the following time and stabilized at comfortable within 3 min at SE, 15 min at LEx, 20 min at MEx and 30 min at HEx conditions.

Fig. 9a shows TA votes, ranging from “Very unacceptable (−4) to “Very acceptable” (4). The profiles of TA and TC votes are similar, but the magnitudes are different. The subjects felt thermally acceptable (2.2) during the 30 min baseline exposure. TA was “just acceptable” (0.4) when subjects had just entered into Room B. TA continuously decreased during the exercise phase. At the end of the phase, subjects were still on the just acceptable level (0.1) for SE, but for LEx, MEx, and HEx, subjects were on the unacceptable side of the scale (−0.6, −1.1 and 1.9 respectively). During the Post-exercise, TA immediately jumped to the positive side of the scale right after entering Room A, for all met conditions. TA reached stability in 5 min at SE and LEx, and 30 min for MEx and HEx.

The percentage dissatisfied (PD) was determined based on the acceptability (TA) votes. When the acceptability vote was negative, it is counted as dissatisfied. The PD at each condition is shown in Fig. 9b. During the 30 min baseline exposure, PD was lower than 10% at all conditions. Upon entering Room B (30 °C) from Room A (26 °C), PD immediately rose to 30%. PD continuously increased during the 15 min exercise-exposure period, reached 53%, 66%, 76% and 86% for SE, LEx, MEx, and HEx at the end of the period. Post-exercise, PD went below 20% immediately after subjects returned to neutral Room A (26 °C) for SE and LEx. However, it took longer, about 5 min, for PD to drop below 20% for MEx and HEx, and return to pre-Ex level after 30 min.

Fig. 10 shows the percentage of subjects voting on the thermal preference scale (I want to be “cooler, no change, warmer”). There was no significant difference between all conditions in the pre-exercise phase. The percentages of “prefer cooler” are between 20%–40%. Subjects generally preferred to be cooler (more than 90%) after entering into Room B (30 °C) as well as at the end of the exercise phase. In the first 10 min of the Post-exercise period, over 50% of subjects still preferred a cooler environment. The greater the exercise level, the more the subjects preferred to be cooler in the early post phase. After 30 min, the percentages of the preferring-cooler population were the same for all test conditions, and continuously declined in the following 30 min, reaching around 20% which is slightly lower than the baseline values.

Fig. 11 shows the percentage of subjects voting on the air movement preference scale (AMP, votes on “prefer more”, “prefer less”, “prefer no change”). Similar to the percentage preferring cooler, there were still more than 20% subjects wanting more air movement in the baseline, and it increased to over 90% in the exercise phase at all activity conditions. Post-exercise, the percentage of preferring more air movement fell to the baseline level in 5 min for SE. For LEx, MEx, and HEx, it took about 20 min to AMP to return to pre-exercise level.

Fig. 12 shows a large variation in perceived exertion on the Borg scale. Overall, the study's range of metabolic conditions produced

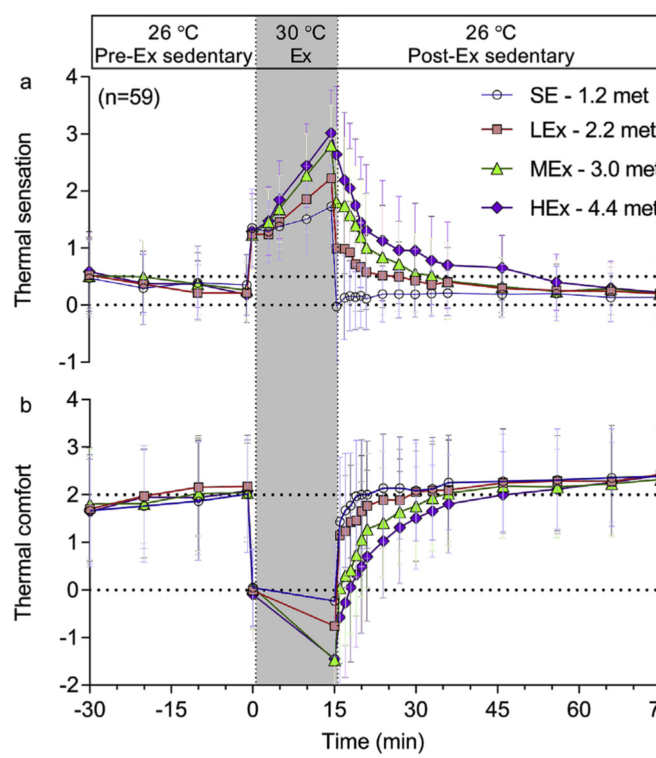

Fig. 8. Mean (a) thermal sensation (TS) and (b) thermal comfort (TC) votes. Error bars show SD.

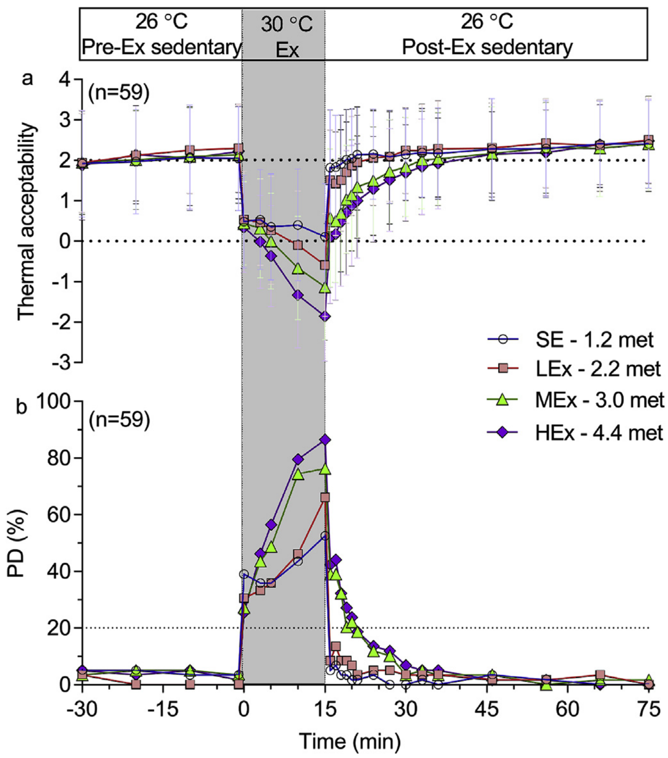

Fig. 9. Thermal acceptability (TA) votes and (b) percentage dissatisfied (PD). Error bars show SD.

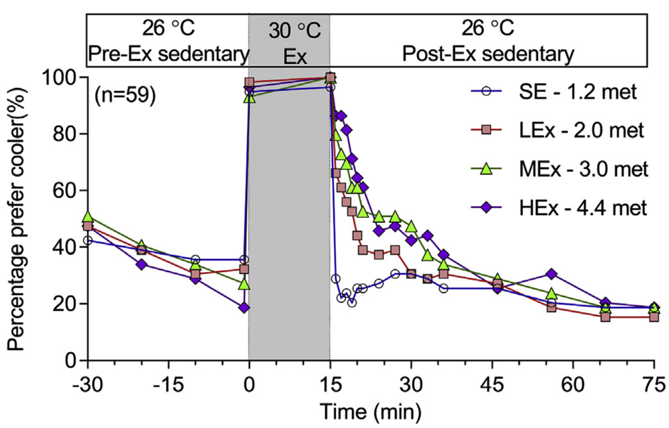

Fig. 10. Percentage want to be cooler.

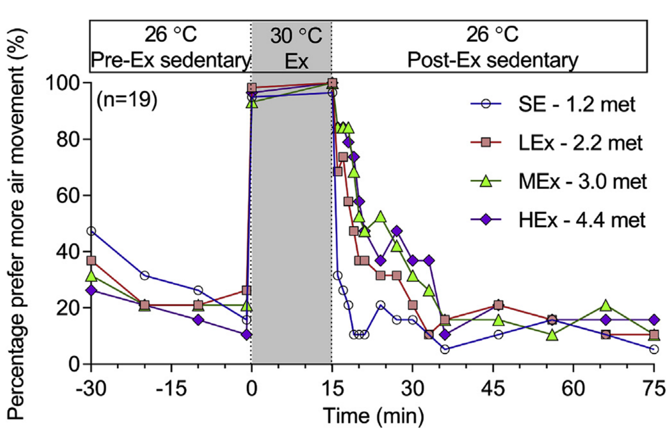

Fig. 11. Percentage wanted more air movement.

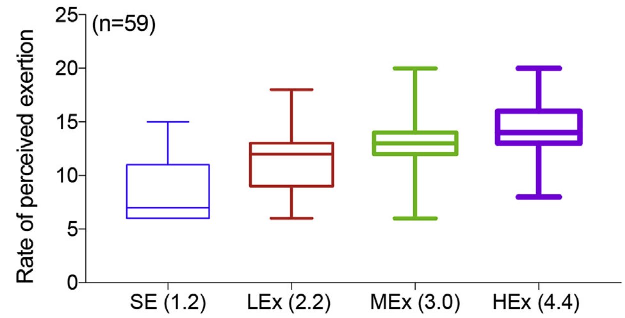

Fig. 12. Rate of perceived exertion on Borg scale.

significant differences in perceived exertion at each test conditions. Subjects median perceived exertion were respectively 7, 12, 13, 14 at SE, LEx, MEx, and HEx conditions, corresponding to "very light", "fairly light", "somewhat hard" and "hard" effort.

4. Discussion

In people's daily life, they commonly experience temperature changes between indoors and outdoors. They also experience changes in their metabolic rate as they move. Unlike previous studies of human thermal comfort during temperature step-changes, this study addresses the effect of both temperature and metabolic rate changes. Our results indicate a significant effect in thermal experience induced by elevated exercise on both the immediate and subsequent human thermal responses, physiologically and subjectively.

A key finding of the present study is that the time needed to return to thermal sensation neutrality (mean TS between -0.5 and $+0.5$) after temperature and metabolic transients depend on previous activity levels. For continuous sedentary activity, the subjective thermal sensation and thermal comfort quickly returned to the baseline value after the temperature down-step. Higher metabolic rates however significantly extended the recovery time; with the higher activity levels requiring longer times to return to neutral. It required 8, 40, 50 min for 2.2, 3.0, and 4.4 met respectively. Compared to thermal sensation, subjects were able to reach thermal comfort (mean thermal comfort votes higher than 0) more rapidly (1–3 min) when returning to the neutral environment. PD also went below the 20% threshold faster (1–5 min) than TS. This indicates that after the thermal stress caused by exercising in a warm environment, entering the neutral environment provided immediate relief of thermal stress (alliesthesia) soon after the transient. However, despite the shorter recovery time for thermal comfort, it still took 10–50 min for subjects to reach the same thermal sensation level as in the pre-exposure phase, depending on the intensity of previous activity levels.

Compared to studies addressing only temperature down-steps [7–10], our findings at 1.2 met (SE-control condition) were similar. However, after exercise, there were marked differences in the time needed to return neutral. This is mainly due to heat stored in the body during exercise in a warm environment, as evident in the increase in T_b after the 15 min exercise (Fig. 5c). Heat was stored when the rate of heat loss lagged the rate of heat production [20]. After the onset of exercise, metabolic rate tended to increase immediately (Fig. 4a). However, sweating, the main source of heat loss in such conditions, only initiated slowly after onset of exercise and could not reach a steady level after 15 min exercise (Fig. 6). This finding is in line with a classical study by Saltin et al. [12], which suggested that sweating only caught up with metabolic heat production after at least 10 min during moderate exercise, and longer for vigorous exercise. Consequently, the higher the previous metabolic level, the higher the T_b (body heat storage) when exercise stopped, and the longer the time for the body to return to neutral. Because the heat stored in the body needs this period to disperse, thermal sensation continued to be warm over 20–30 min in the recovery phase. Skin wettedness did not return to the base condition within 60 min for any of the three exercise levels.

These findings could shed light on the findings in previous field studies of spatial transition from outdoors to indoors [33–36]. They generally found that occupant (visitors) who just arrived the buildings tended to feel warmer than those who stayed longer. These studies tended to associate thermal sensation and comfort after entering the buildings in the first 20 min with outdoor temperatures. Our findings suggest that the warm sensation was mainly due to the elevated metabolic rates of the previous activities, rather than previous outdoor temperatures. We demonstrate that the temperature difference alone between outdoors and indoors did not cause occupants to remain thermally unacceptable after entering the neutral room (the SE - 1.2 met case), rather, they perceived the neutral room as cooler-than-neutral immediately after the transient. It was the heat storage induced by the elevated metabolic rate in warm outdoor temperatures that made occupants feel warmer during the indoor exposure. Also, they may have felt uncomfortable due to elevated skin wettedness although we did not survey skin wettedness perception.

This study provides two significant findings pertaining to building operation. 1) Although the air conditioning temperature of 26 °C in summer is not cool enough to make people's thermal sensation return to neutral quickly right after the metabolic exertion of commuting, thermal comfort and acceptability returned to positive quickly within 2 min. 2) As evident in Fig. 11, a large number of subjects prefer more air movement in the first 20 min after exercise, during the same time that they were also preferring a cooler environment (Fig. 9), probably due to the elevated core temperature and skin wettedness in the post-exercise period. Providing air movement has been proved to be a very effective way to restore thermal comfort after exercise [22,37,38] by enhancing convective and evaporative heat loss from the human body. Therefore, it is desirable for fan cooling to be available in the early stage of the recovery process, for example in the building's lobby or entrance areas where the metabolic and temperature step change transients begin. Having fan cooling available may be desirable at the office workstation as well. Future studies would be needed to explore the effectiveness of air movement on maintaining comfort in different room setpoint temperatures after exercise metabolic transients. Also, it would be helpful to investigate the effectiveness of personalized comfort systems (PCS) at different indoor setpoint temperatures [39].

This study addresses thermal comfort effects experienced after entering an office environment following four different rates of exercise in a warm environment. Restricted by experimental conditions, the exercise simulations did not include all the relative air motions generated by actual walking or cycling. A follow-up field study will help to examine those effects for a few realistic cases. We also plan another lab study with varying levels of air speed applied to the subjects during the simulated outdoor exercise and during the transition to indoors. Due to limits in time and resources, our study only addressed one temperature step-change. The effect of combinations of multiple thermal environment parameters (temperature, humidity, wind speed, solar radiation) will need to be explored in the future. Due to experimental limits, it was not possible to precisely monitor the amount of body heat storage, or the evaporative heat loss. Therefore, a heat balance model could not be established in the current study. This could be done in the future by using simultaneous direct and indirect calorimetry [40–42] in future studies.

Finally, whether people would have different expectations from participating in a lab study versus real life, and how the difference might affect comfort perceptions, are general questions that deserve further study. Our unburdened student subjects may have been more accepting of elevated temperatures than workers in actual offices. We believe the field study can be designed to help answer these questions.

5. Conclusions

We have investigated the effects of a range of activity levels caused by commuting in heat (30 °C) on human physiological and comfort responses after entering a neutral room (26 °C) and resuming sedentary activity.

We show that a short period of elevated metabolic rate in the heat has significant effects on human physiological and subjective responses during and after the metabolic changes. During exercise, metabolic rate responses were prompt in elevating to stable conditions from pre-exercise levels (2–5 min), while sweating responses (represented by skin wettedness, Fig. 6) was slower and could not reach stable conditions even after 15 min exposure. This discrepancy between heat generation and the main avenue of heat loss results in heat storage during the commute, which leads to elevated core temperature, body temperature, and skin temperature by the end of the exercise phase. During exercise, subjective thermal sensation was also elevated from the baseline, while thermal acceptability significantly reduced.

Post-exercise, the stored body heat needed time to dissipate before the body recovered to neutral state and thus delayed the time for thermal sensation and comfort returning to pre-exercise level. For SE, where there was no heat storage, temperature step change from 30 °C to 26 °C result in immediate TS and TC recovery. The time for human thermal sensation to be restored to its pre-commute baseline level depended on the activity intensities. The higher the commute activity (2.2 met, 3.0 met and 4.4 met), the longer it took for thermal sensation to reach thermal sensation neutrality. For MEx (3.0 met), and HEx (4.4 met), the time for TS to come below 0.5 were 0, 8, 17 and 30 min, and were 0, 30, 40 and 50 min to reach pre-Ex levels. These are significant periods for building controls indoors; so that after the metabolic down-step of a commute, people will be requesting cooler ambient temperatures that would likely be too cold for the people already working in the building. In addition, skin wittedness, which by itself represents a source of discomfort, remained elevated throughout the 60 min indoor period.

Most subjects preferred to be cooler and to have more air movement in the post-exercise period. To save energy while maintaining comfort for occupants in the down-step after a commute, it is suggested that personal thermal comfort devices, such as fans, could be provided to rapidly evaporate sweat, extract body heat, and enhance thermal sensation and comfort.

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Appendix. Survey questionnaires

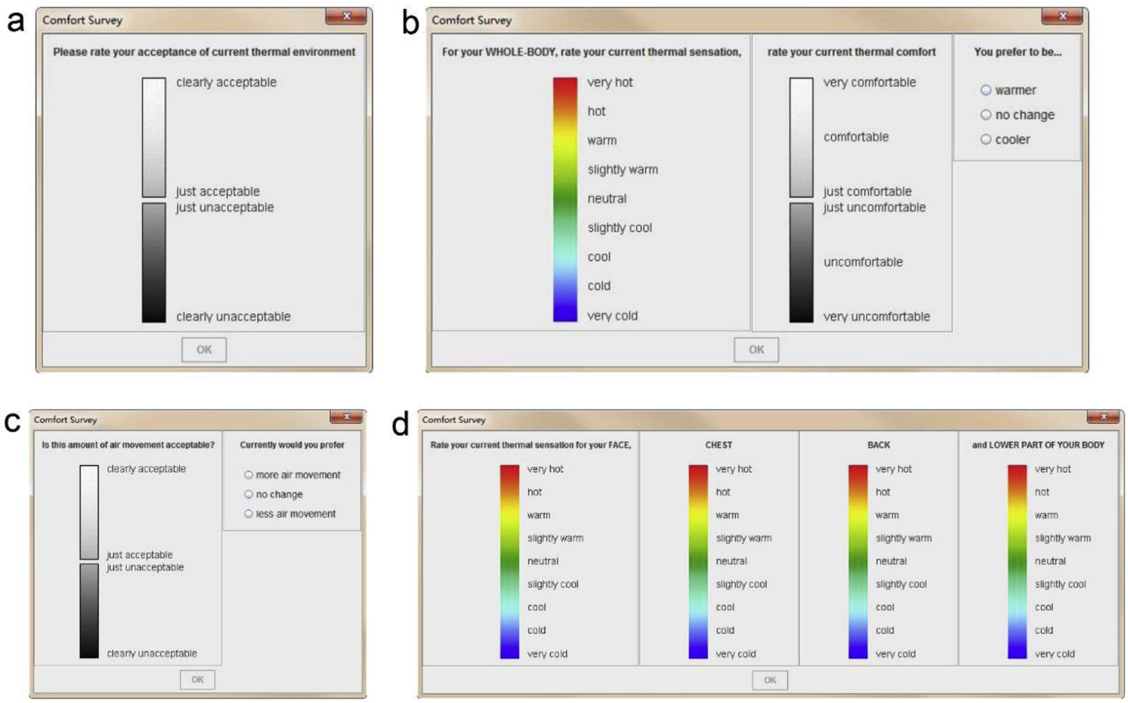

Fig. A1. (a) Thermal acceptability, (b) thermal sensation, thermal comfort and thermal preference, (c) air movement acceptability, air movement preference, (d) different areas of thermal sensation

Rate of Perceived Exertion Scale	No Exertion	Extremely Light		Very Light		Light		Somewhat Hard		Hard		Very Hard		Extremely Hard	Maximally Hard
Rating Scale	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Fig. A2. Borg Rating of Perceived Exertion (RPE) Scale

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