Title
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Abstract

People often feel uncomfortably warm and sweaty in their workspace after commuting there by walking or cycling in summer. This is because body heat stored during the commute takes a substantial time to dissipate. People complaining about this uncomfortable transition may cause operators to lower the thermostat setpoint, causing long-term overcooling and wasting energy. In addition, space cooling is slow, requiring minutes to take effect. This study addresses how to improve comfort in the transition by increasing the availability of convective cooling, where the response time is in seconds. Thirty-five subjects (17 men and 18 women) dressed in 0.6 clo entered a test room after exercising at 4.4 met for 15 min in 30 ºC. The exercise emulates the commute activity in summer. The test room was controlled to 24, 26, and 28 ºC, *with* and *without* the option of cooling using fan-produced horizontal airflow. Subjects were sedentary for 60 minutes, during which subjective thermal responses and physiological responses were measured. The enhanced convective and evaporative heat loss caused by fans significantly shortened the time needed to reach thermal comfort after the exercise-induced thermal stress and improved the final comfort level. Compared to a typical indoor condition of 24 ºC and still air, 26 and 28 ºC with fans provided equal or better comfort more quickly, and inherently required much less energy to do so. Our study suggests that personally controlled air movement should be available in spaces where thermal and metabolic down-steps take place.

Keywords: Air movement, summer commute, metabolic down-step transient, thermal comfort, energy saving

1. INTRODUCTION

People are increasingly choosing green and healthy modes of commuting to work, such as walking or cycling [1]. Unlike sedentary riding in vehicles, these more physical activities act to elevate metabolic rate, body heat and sweating [2]. Especially in warm weather, such increases affect people's thermal comfort well after they have entered cooler air-conditioned indoor spaces and become sedentary. Thermal sensation, comfort, and physiological responses all require time to reach steady-state indoor values [3], primarily due to body heat that was stored during the exercise in the heat [4,5].

Current thermal comfort standards, models, and design guidance [6,7] in most part apply only to lengthy periods of sedentary activity. Because commuters retain heat after exercise, indoor temperatures that are appropriate for extended sedentary activity are too warm for quickly establishing thermal comfort during the cooling-off period following entry to the room. As people feel themselves too warm and sweaty during this transition period, they are prone to request the building operators to lower the indoor temperature. Lowering the air temperature in a building is in itself a slow process (taking several minutes to hours at least), and in addition it is slow at cooling the body. The change overcools the other occupants who were already sedentary in the building and comfortable at the initial temperature. Finally, the changed setpoints often are not returned to their earlier settings, result in energy-intensive and uncomfortably overcooled building operation.

It is important to find ways to improve thermal comfort after commuting outdoors and entering offices. Studies in Japan [[8], [9], [10], [11], [12]] and Denmark [13] have described how cooler temperatures and lower humidity improve thermal comfort and shorten the time for occupants to return to comfort. For instance, Bordakis et al. [13] suggested that for places where most occupants commute by bike or on foot, room starting temperatures should be lowered to 20.0–21.5 °C in summer, significantly lower than ASHRAE and ISO comfort zone recommendations. Such temperatures would increase the energy demand for cooling or dehumidification. In addition, since temperature and humidity in the building require time to be controlled, precooling is needed which adds to energy costs and predictive control complexity.

Air movement within the room, on the other hand, can be switched on almost immediately, affects body cooling rapidly, and requires little energy to implement [14,15]. Previous studies in steady state conditions show that air movement significantly improves people's thermal comfort in warm temperatures for sedentary people [[16], [17], [18], [19], [20], [21]] and at elevated metabolic rates [[22], [23], [24]]. Even under thermal stress - 30 °C with moderate activity level (fixed heart rate of 110 beats min−1), air movement with a standing fan were foucould provide better comfort for people doing an arm workout. Furthermore, their subjects also performed better in warm temperature (30 °C) with fans than conditions with air conditioning at 23 °C [25].

Air movement has also been found to significantly improve human thermal comfort after elevated metabolic rates. It could restore thermal comfort in 5 min after taking four sets 20 vertical steps in 10 min in warm-humid conditions [19]. Air movement was also found to perform better to alleviated thermal discomfort than lower down room temperature/humidity after simulated summer commute [11]. This was confirm by a quasi-experimental study from hot-humid Singapore, which found that ceiling fans with varied speed levels could maintain the same level of thermal comfort at 27 and 30 °C as 24 °C with the fan off, after commuting on university campus by walking at different distances and durations [26].

However, there have been few studies on investigating the underlying mechanism of human comfort requirement during thermal transitions induced by a metabolic rate down-step, and finding energy efficient way to restore and maintain comfort after it. In a preceding study [3], the authors examined transient human thermophysiological and comfort responses following exercise levels simulating commutes in the heat. The study showed that after the commutes, although metabolic rate dropped to sedentary within about 2–5 min, the body's stored heat (observed by increased core temperatures) continued to be elevated for 60 min. Thermal sensation also required 30–50 min to recover to the baseline sedentary condition observed before the exercise.

Building upon this previous study, we focus here on the potential of air movement to accelerate the cool-down rate and to shorten recovery time after moderate exercise in the heat. We want to compare physiological and subjective responses of subjects after they have transitioned from a fixed commute scenario into several different indoor temperatures, in each case with and without fan cooling available. The comparisons are intended to inform the design of better and more efficient environmental control strategies in buildings.

2. METHODS

The experiments were conducted in the climate-controlled chambers of Xi'an University of Architecture and Technology in August 2018, during which outdoor temperature was around 26–36 °C.

2.1 Subjects

After approval of the experimental protocol by the Xi'an University of Human Research Ethics committee. Thirty-five healthy university students (17 males, 18 females) consented to participate in the experiments. Their anthropological data are shown in Table 1.

2.2 Experimental conditions

The subjects dressed in uniform (0.6 clo) provided by the research group, which contains a cotton long-sleeve shirt, thin straight trousers, underwear, light socks, and sports shoes. Mesh chairs were used to minimize the additional insulation of the chair.

The experiments were designed to represent a workday commute scenario in which people leave their home and walk or cycle to their office on a summer morning. Three rooms were used (Fig. 1a). Room A was controlled around 26 °C to represent a neutral home temperature setting; Room A was also used for subjects to take rests between tests to minimize the effect of previous thermal experience. Room B was controlled at 30 °C, 50% RH to represent a typical summer outdoor condition, while Room C was controlled to three different setpoint temperatures (24, 26 and 28 °C) and 50%RH to represent different office setpoint temperatures. Four subjects were tested at a time. Personally controlled fans with 32 speed settings were installed in the room, providing horizontal air flows toward each subject (Fig. 1b).

Table 1 Subjects' anthropology data

	Males	Females	All
Sample size	17	18	35
Age (yr)	21.9±1.8[a]	21.4±1.6	21.6±1.7
Height (m)	1.75±0.06	1.64±0.06	1.70±0.08
Weight (kg)	66.5±6.9	54.4±5.9	60.3±8.8
BMI[b]	21.6±2.2	20.4±2.1	21.0±2.3

[a]SD; [b]Body Mass Index=weight (kg)/[height (m)][2]

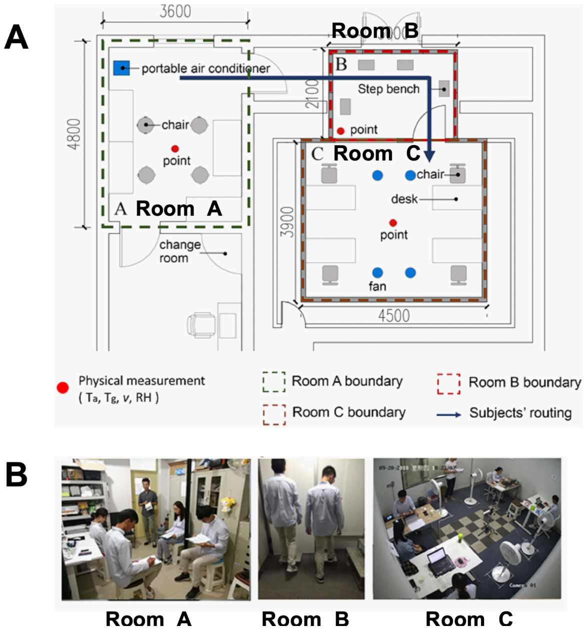

Fig. 1. (a) Floor plan (b) Chamber setting (from left to right: Room A, B, C)

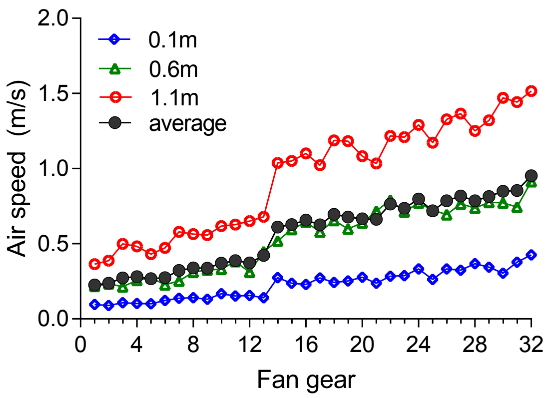

Fig. 2. Measured air speed at each fan level

Overall, six test conditions were tested, namely 24, 26 and 28 °C without fans, and the same three temperature settings with fans. For conditions with fans, the fans were turned on initially at 12 (0.65 m/s), 15 (1.05 m/s) and 18 (1.19 m/s) settings, at 24, 26 and 28 °C respectively.

Tests were randomized to avoid sequence effects.

2.3 Instrumentation

2.3.1. Climate chambers

Fig. 1 shows the experimental set-up. Room A (measuring 4.5 m × 3.6 m × 3.3 m) was controlled by a portable air conditioner. Relative humidity was not controlled but remained approximately 50%. Room B and C control temperature to an accuracy of ±0.2 °C, and RH was maintained at 50% RH ± 5% by a dedicated heating and cooling system. Air was supplied from the ceiling and returned from the lower side (Room B) or under floor (Room C). Mean radiant temperature was controlled to be equal to air temperature by turning on the chamber 3 h before the experiment, and controlling the temperature the annular space between the chamber and walls the same as the chamber. Air speed was less than 0.1 m/s. Room C, where subjects spent most of their time (1hr), was ventilated with an outdoor flow rate around 90–100 L/s. Sufficient to satisfy the ventilation requirements for occupants. During the test, the number of occupants was 5–6 (four subjects and one or two experimenters), and the measured CO2 level was around 600 ppm.

2.1.2. The fans

The direct-current fan is very energy-efficient commercial product, consuming only 1.7–17 W for fan speed settings 1 to 32. Each fan was placed 1.2 m away from the position of the subject and was controlled by the subjects with a remote controller. Air speeds (measured at 1.1 m height at the subjects' locations, without occupant) increased from 0.37 m/s to 1.52 m/s between levels 1 to 32 (Fig. 2).

2.1.3. Physical measurements

Environmental parameters were measured with laboratory grade equipment to assure that the test chambers were controlled to the experimental design. The equipment was placed in the center of the climate chamber. All physical parameters were sample every 1 min throughout the tests.

The details of equipment for physical parameter measurements are summarized in Table 2. Air temperature/relative humidity were measured at three heights (0.1 m, 0.6 m, 1.1 m) using sensors TD/TR-72ui, T&D Corp., Nagano-ken, Japan, temperature accuracy ± 0.3 °C, RH accuracy ±5%. Globe temperature was measured at 1.1 m height (HQZY-1, TianJianhuayi Co., Ltd, Beijing, China, accuracy ± 0.3 °C). Air speed was measured at the three heights with omnidirectional hot wire anemometers.

Table 2 Physical parameters measuring equipment

	Equipment	Accuracy	Location
T_a, RH	TD/TR-72ui	± 0.3 °C, ±5%	0.1 m, 0.6 m, 1.1 m
V	WFWZY-1	± 0.05 m/s	1.1 m
T_g	HQZY-1	± 0.3 °C	1.1 m
Fan power	UX120-018	± 0.5%	-

(WFWZY-1, TianJianhuayi Co., Ltd, Beijing, China, accuracy± 0.05 m/s). Measurements were made both before and after the test to characterize the air speeds at each workstation for each of the available fan speeds. During the tests, the fan power was measured with plug load logger (UX120-018, HOBO

Corp., Massachusetts, USA, accuracy ± 0.02 W), to determine the fan speed levels from which the air speeds at the workstation could be derived.

2.1.4. Physiological measurements

As shown in Table 3. The metabolic rate (Met) profiles generated by the experimental sequences were quantified with 9 subjects, using a wearable metabolic measurement system (COSMED K5, COSMED S.r.l., Italy). The K5 was calibrated on gas sensors, flow rate, and pressure before each testing. It uses a face mask that covered both the mouth and the nose to collect expired gas from the subjects, and the captured gas was analyzed in micro-dynamic mixing chamber provided oxygen consumption rate (VO2), carbon dioxide output (VCO2), ventilation (VE), and respiratory exchange ratio. The metabolic rate was then determined using ISO 8996 method [27].

Table 3 Physiological parameters measuring equipment

	Equipment	Accuracy	Location
T_{sk}	iButton DS1922L	± 0.1 °C with calibration	chest, forearm, thigh, and shin
Skin RH	iButton DS1923	± 0.1 °C with calibration, ±3% RH	chest, forearm, thigh, and shin
Met	COSMED K5	±0.02%	-
SBF	PeriFlux 5000	± 10 PU	forearm
HR	Polar H10	±5 beat	chest

Heart rate (HR) was sampled every 10 s by a Polar heart rate sensor (Polar H10, Polar Electro Oy, Kempele, Finland.

in temperature (Tsk) and skin RH were sampled every 1 min throughout the experiment. Skin temperature was measured using wireless temperature sensors (Pyro Button-L, Opulus Ltd, PA, USA). The measuring points were arranged on the chest, forearm, thigh, and shin. Mean skin temperature was calculated as an area-weighted average of measurements using equation (1) [28].

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

The temperature and relative humidity in the space between the skin and clothing was measured using small wireless temperature and relative humidity sensors (Hygrochron iButton, Maxim, USA). Accuracy is ±2% RH over the range 0–100% RH with a time constant of 30 s. Sensors were housed inside a short length of plastic tubing. When taped to the body, the sensors were positioned less than 3 mm above the skin surface and exposed through the open end of the tubing, enabling the measurement of temperature and relative humidity just above the skin surface. The measuring points were arranged on the chest, forearm, thigh, and shin. Mean skin wettedness (w) was calculated as an area-weighted average of measurements using the following equation [29].

$$w=0.3*w_{arm}+0.3*w_{chest}+0.2*w_{thigh}+0.2*w_{shin} \quad (2)$$

Skin wettedness (w) was calculated using the following equation, adapted from Kerslake [30].

$$w = (P_m - P_a) / (P_{ssk} - P_a) \quad (3)$$

where

P_m vapor pressure at the skin surface

P_a ambient vapor pressure

P_{ssk} saturated vapor pressure at skin temperature

Ambient vapor pressure is considered to be constant around the body and is based on the average temperature and humidity of the surrounding air. Pm, the vapor pressure at the skin surface, is based on the measurement of the temperature and relative humidity in the space between the skin and clothing. Pssk, the saturated vapor pressure at skin temperature, is calculated from the measurement of the skin temperature.

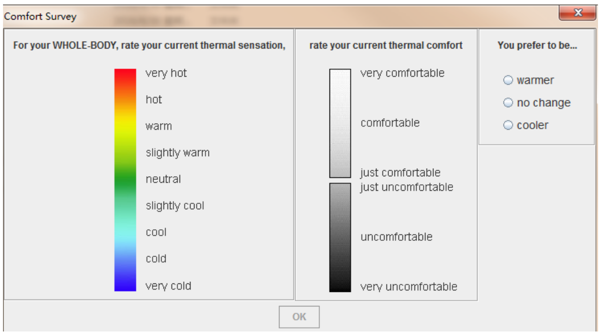

Fig. 3. Sample survey rating scales

2.4 Questionnaires

A paper-based survey was administered when subjects were in ROOM A and ROOM B. Subjects rated their thermal sensation (TS), thermal acceptability (TA), thermal comfort (TC), thermal preference (TP), air movement acceptability (AMA), and air movement preference (AMP) responses on radio button scales. In addition, comfort surveys (Fig. 3) repeatedly appeared on a computer on each subject's workstation when subjects were in ROOM C. They appeared at predefined time intervals to obtain instantaneous thermal sensation, thermal preference, and other comfort factors. The TS scale units are −4 very cold, −3 cold, −2 cool, −1 slightly cool, 0 neutral, 1 slightly warm, 2 warm, 3 hot, 4 very hot. TA, TC, 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 (TP) (−1 want cooler, 0 no change, 1 want warmer) and air movement preference (AMP) (−1 want less, 0 no change, 1 want more). Surveys were administered for each condition according to the experimental procedure (Fig. 4).

2.5 Experimental procedure

Before the main experiments, pilot tests on 4 subjects were conducted to validate the feasibility of the design. Subjects arrived at the test chamber in groups of 4 for each test. Before the test, all subjects attended a training session to get familiar with the chambers, test process, control of fans, and survey questions.

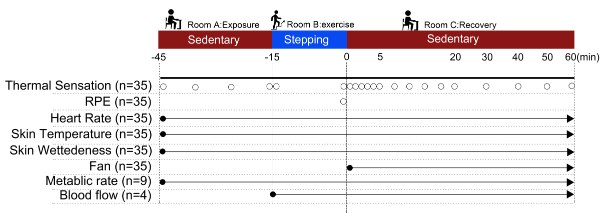

Fig. 4. Experimental procedure

Subjects were asked to avoid performing intensive exercise or consuming alcohol or caffeine-containing drinks 24 h before the test. Fig. 4 shows the test procedure used in this study. The subjects were asked to arrive 20 min before the test to change into test uniforms and secured the temperature sensors and HR belt to their bodies. The subjects in each experiment were exposed to around 26 °C (Room A) for 30 min to simulate a neutral at-home condition, after which they entered the second climate chamber (Room B) and performed stepping exercises for 15 min (30 steps/min, 4.5 met) to simulate moderate outdoor exercise; at the end of this period they walked back to the Room C, and remained sedentary for 60 min until experiment ended. Survey questionnaires were administered every 10 min during the first 30 min exposure, right before and after the exercise, every 1 min after the exercise repeated 5 times, then every 3 min from the 21st to the 36st minute, then every 10 min until the end of the test.

2.6 Statistical analyses.

The observed physiological and subjective responses for each subject are averaged, with only mean values reported in the paper. Statistical analysis was performed using Graphpad Prism 7 for Windows (GraphPad Software, San Diego, California US). The experiment was treated as a repeated measures design. Differences between Fan and No-fan cases were tested using repeated-measures analysis of variances (RM-ANOVA) with post-hoc analysis to test the difference at each time point. Percentage data were tested using the Chi-square test. Data are reported in mean ± SD (standard deviation). Significance is accepted at 0.05.

3. RESULTS

3.1 Fan usage

Fig. 5 shows the fan power, airspeed, and fan-use during the tests. Fan power was monitored continuously and converted to corresponding fan speed levels, and finally to air speed. Measured air speeds are at the 1.1 m height.

An average subject's fan power consumption was highest around 5–9 W at first, decreasing to 2–5 W at the end of the exposure. At higher temperature settings subjects chose higher mean air speeds, and more subjects used fans, resulting in higher fan power consumption (Fig. 5a). Preferred air speed peaked at 0.8–1.0 m/s immediately after entering Room C, after which it decreased and stabilized at 0.35, 0.50 and 0.75 m/s at 24, 26, and 28 °C, respectively (Fig. 5b). Fan use rate was 100% at the beginning, gradually decreasing until the end of the exposure, to 83%, 60%, and 31% at 28, 26, and 24 °C respectively (Fig. 5C).

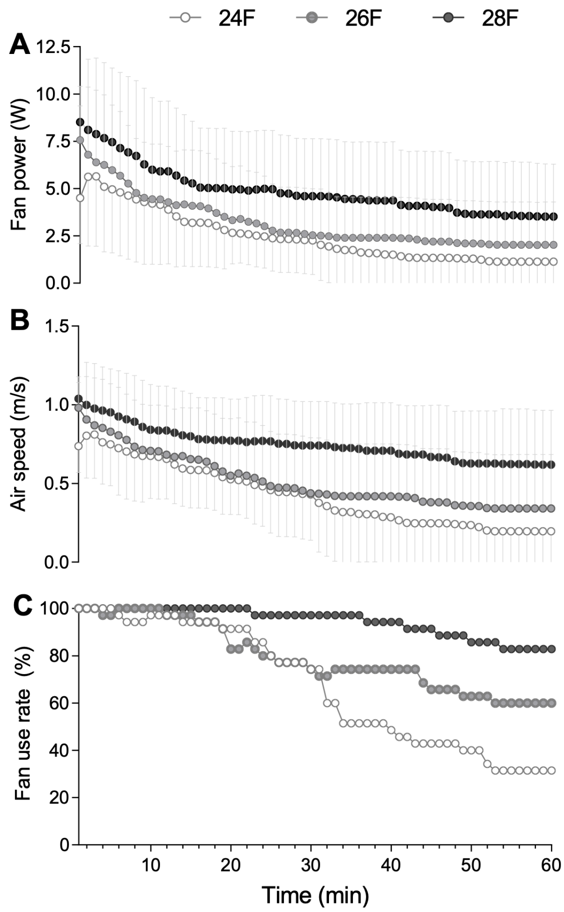

Fig. 5. Fan power (a), air speed (b), and percentage fan use (c). Error bars show SD.

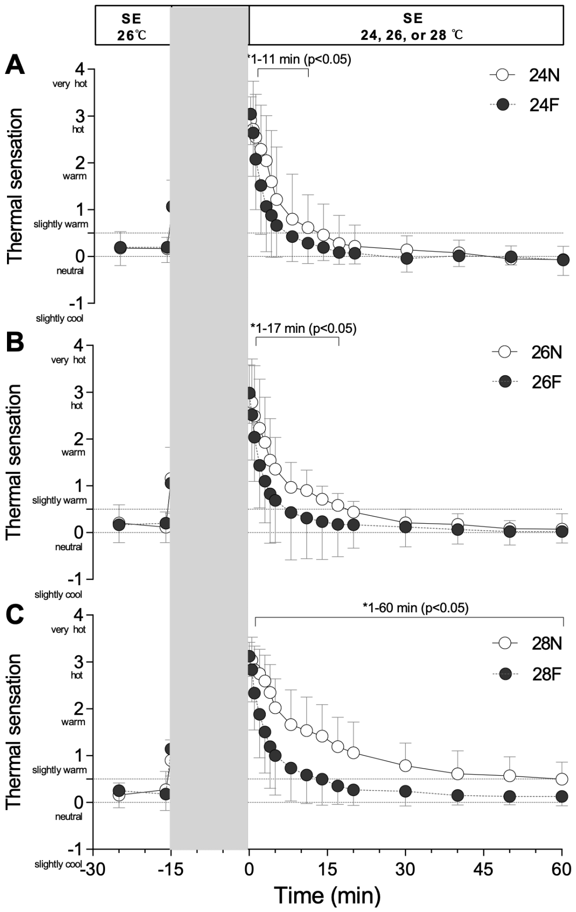

Fig. 6. Thermal sensation votes for all test conditions. Data show mean (Black – Fan, White – No fan). Error bars show SD. Asterisk (*) indicate significant differences between Fan and No fan.

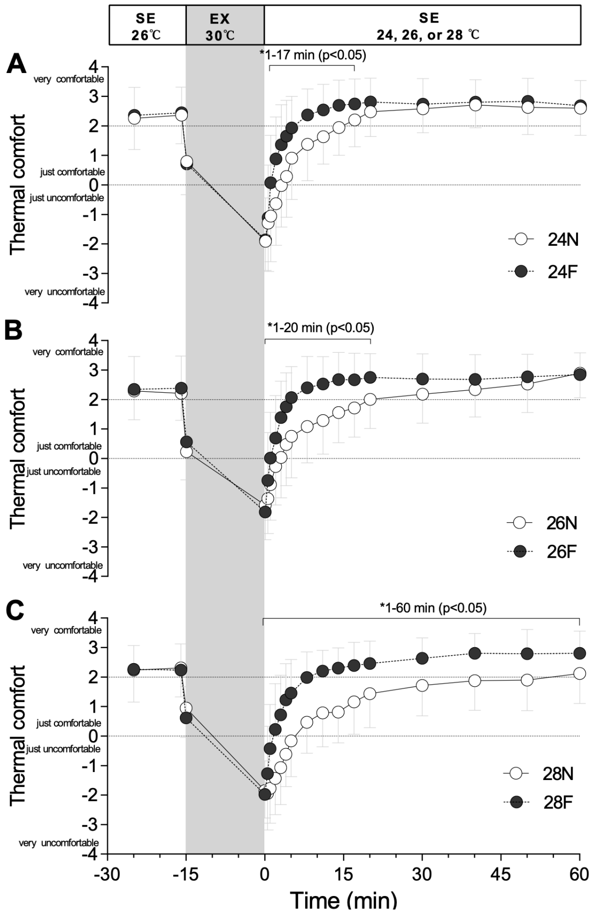

Fig. 7. Thermal comfort votes for all test conditions. Data show mean (Black – Fan, White – No fan). Error bars show SD. Asterisk (*) indicate significant differences between Fan and No fan.

3.2 Subjective responses

Fig. 6 presents the overall TS votes in each condition. Baseline TS was neutral (0.1–0.2). The initial exposure to 30 °C in Room B increased TS to 1.0 (slightly warm). The 15 min exercise in 30 °C elevated TS to 3 (hot).

In all test conditions, TS votes began to drop as soon as subjects entered Room C. Air movement significantly reduced this TS. Compared to the same conditions without fans, TS was significantly lower for the first 10 min at 24 °C, first 16 min at 26 °C, and the entire hour at 28 °C. Without air movement, it took about 13, 19, and 60 min for TS to reach neutral (TS = 0.5), and about 25, 40 and more than 60 min to reach pre-exercise baseline levels at 24, 26, and 28 °C. With air movement, however, the time to return to neutral was significantly shorter, 7 min for 24 °C, 7 min for 26 °C, and 8 min for 28 °C.

After the transient down-steps, the thermal sensation profiles are very similar for the three tested ambient temperatures (24, 26, and 28 °C). The fan has a dominant effect on thermal sensation at these temperatures. Most significantly, the thermal sensation recovers faster at 26 and 28 °C with fans recovers faster than at 24 °C.

Fig. 7 shows the thermal comfort (TC) votes at each test condition, ranging from "Very uncomfortable" (−4) to "Very comfortable" (4). Baseline TC was comfortable (2). A sharp 0.5–0.8 scale-reduction in TC happened as subjects entered the warm ambient temperature room B, reducing further to −2 after exercising in 30 °C. Entering the cooler Room C, TC

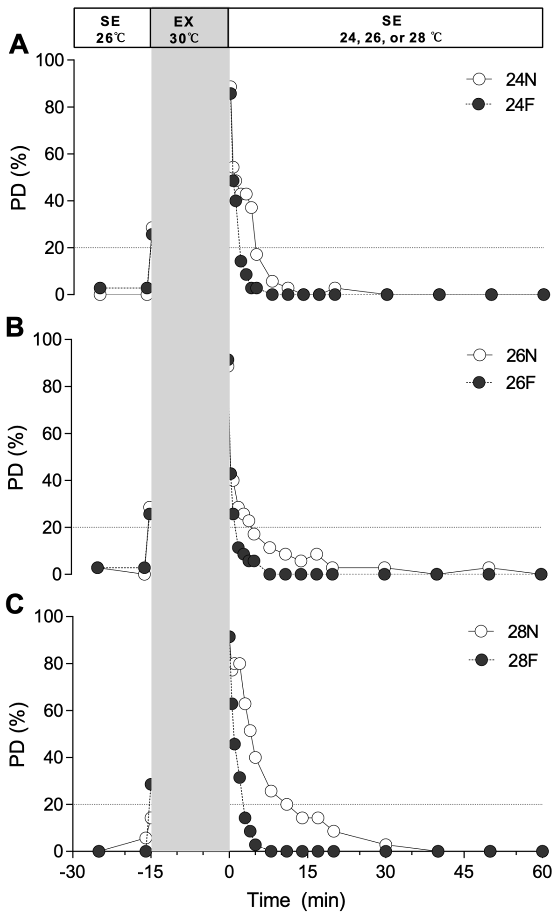

Fig. 8. Percentage dissatisfied (PD) (Black – Fan, White – No fan).

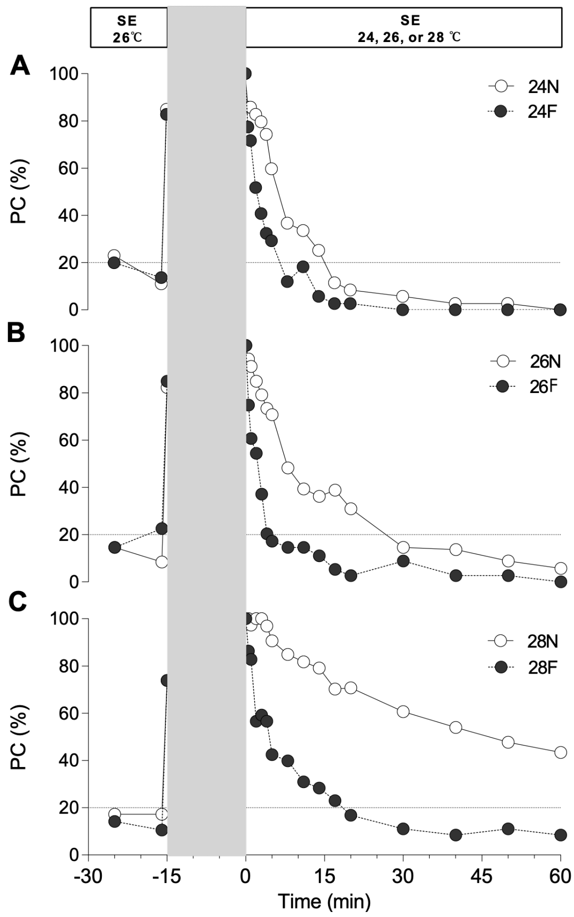

Fig. 9. Percentage preferred to be cooler (PC). (Black – Fan, White – No fan).

rapidly returned to the comfortable side of the comfort scale rapidly. Compared to conditions without fans, fans significantly improved TC in the first 17 min, 20 min, and 30 min at 24, 26, and 28 °C, respectively. All conditions with fans show a much faster recovery time than those without fans. Without fans, even at the low 24 °C room temperature, 15 min were required for TC to return to the baseline level, while it took only 6 min with fans. For 26 °C, the recovery time was 20 min without fan versus 6 min with fan, and for 28 °C, the recovery time was 60 min without fan versus 7 min with fan.

Fig. 8 shows percentage of dissatisfied (PD). The baseline PD was lower than 5% for all test conditions. PD increased to around 30% immediately after entering 30 °C, and continued to increase to 90% at the end of the exercise. Entering the cooler temperature significantly reduced PD, going below 20% in 3, 3, and 4 min at 24, 26, and 28 °C with the fan. It took twice the time for PD to drop below 20% for conditions without fans: 6, 6, and 12 min at 24, 26, and 28 °C.

Fig. 9 shows the percentage of subjects preferring to be cooler (PC). There was no significant difference between all conditions at baseline or during exercise. Subjects generally preferred to be cooler after entering 30 °C (about 80%) as well as finished exercise (about 95%). PC went down gradually after exercise and entering the cooler room. It took significantly less time for PC to go below 20% with fans (7, 6, and 20 min at 24, 26, and 28 °C), compared to 15, 30, and more than 60 min respectively without fans. PC remained above 20% at the end of 28NF exposure (40%).

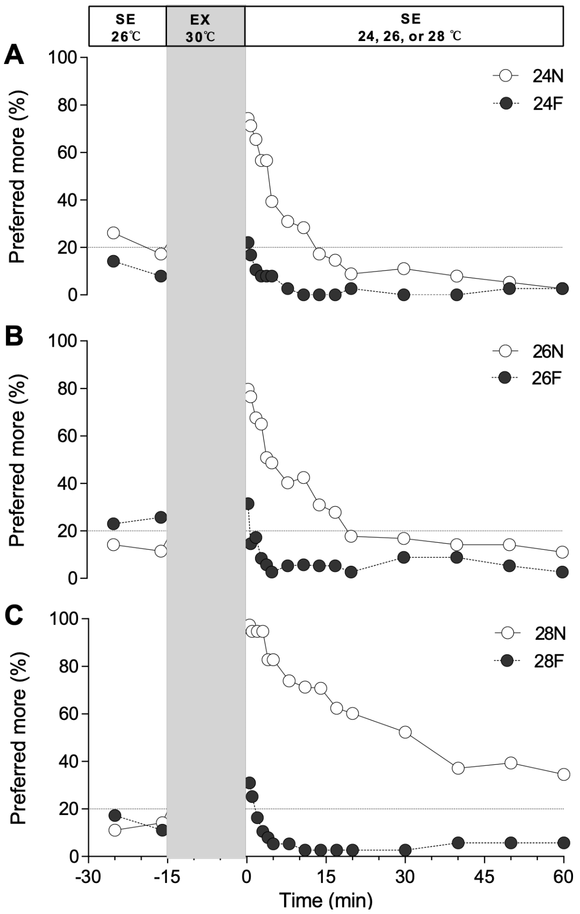

Fig. 10. Percentage preferred more air movement. (Black – Fan, White – No fan).

Fig. 10 shows the percentage of subjects voting that they prefer more air movement (PM). There was no significant difference in PM between test conditions at pre-exposure. Without fans, subjects preferred more air movement following exercise. Fig. 10a shows that PM went below 20% immediately after subjects came to 24 °C room with fan (~1 min), while it took much longer for PM to drop below 20% at 24 °C without fan (15 min). This shows that even in this neutral or slightly cool ambient environment, people prefer more air movement for the first 15 min after the summer commute. Fig. 10b shows that PM took 2 min to go below 20% at 26 °C with fan, while it took 21 min for PM to drop below 20% at 26 °C without fan. During the entire hour at 28 °C, a large number of subjects without fans wanted more air movement (Fig. 10c), while with fans it took about 2 min.

3.3 Physiological responses

Fig. 11. Metabolic rate (a) and heart rate. Error bars show SD the whole process (Fig. 11a). Fig. 11b shows HR as observed during the experiments. Baseline sedentary. HR was 80 ± 10 beats/min. Heart rates changed within 1 or 2 min after the onset of exercise, and continue to increase during the 15 min of exercise. HR was 137 ± 17 beats/min at the end of the exercise. HR decreased to the baseline level in approximately 5 min. There were no significant differences in HR between any of the temperature or fan test conditions. However, each condition with fans shows faster HR recovery than without fans.

Fig. 12 shows that after 30 min of pre-exposure, Tsk stabilized at 33.6 °C. Tsk started to rise immediately following the subjects' metabolic increase. During exercise, Tsk increased to 34.5 °C, about 0.9 °C higher than the baseline value. Following the subjects' entry to Room C, the fan immediately reduced Tsk, reaching a stable level in about 7 min, which remained 0.6 °C lower than the Tsk without fan for the remaining 60 min. Without the fan, Tsk continued to increase for 3–5 min after entering the room, approaching 35 °C at 26 and 28 °C ambient. Tsk then decreased and reached a stable value in 14 min. Interestingly, this 3–5 min spike and delay in reducing Tsk after entering Room C is not reflected in the thermal sensation and thermal comfort votes in Fig. 6 and 7, which begin to recover immediately after entering the room, whether there is a fan or not.

Fig. 13 shows skin wettedness (w). The baseline w stabilized at 0.2 to 0.25. It began to rise immediately after the subjects' metabolic rate changed, increasing to 0.6 at the end of the exercise period. After the stepdown transient, for each test condition, w with fans was significantly lower (about 15%–20% lower) than that without fans for most of the time in the recovery period. Without fans w first continued to increase after entering the cooler room, with the greater increases at the cooler temperatures. w needs a longer time to return to baseline level than skin temperature. With fans, about 45 min was required for w to reach the baseline value. Without fans, w did not reach the baseline value within the entire hour under either the 26 and 28 °C ambient conditions. With fans, w was lower at 26 and 28 °C than without fans at 24 °C.

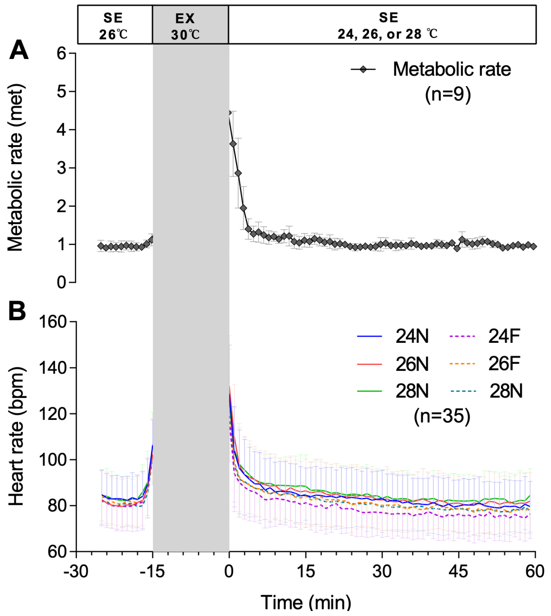

Fig. 11. Metabolic rate (a) and heart rate. Error bars show SD

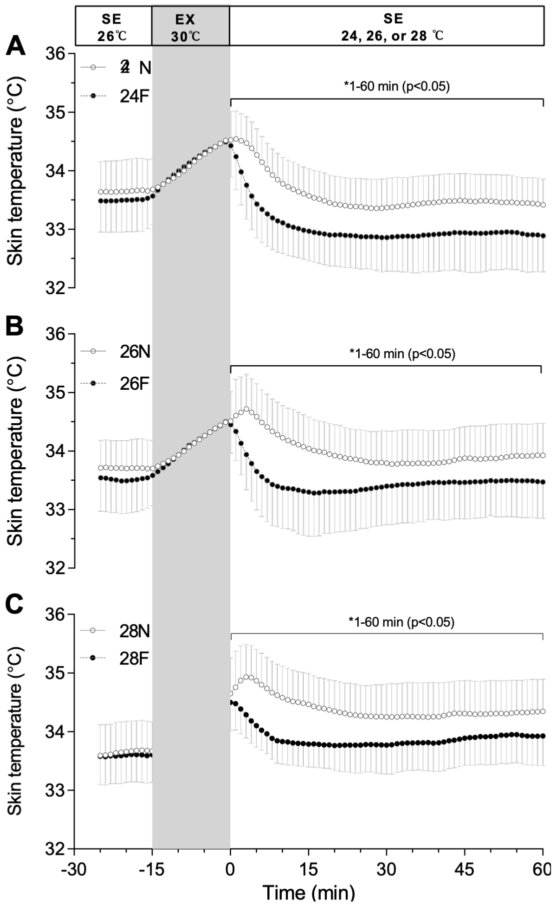

Fig. 12. Mean skin temperature. Data show mean (Black – Fan, White – No fan). Error bars show SD. Asterisk (*) indicate significant differences between Fan and No fan.

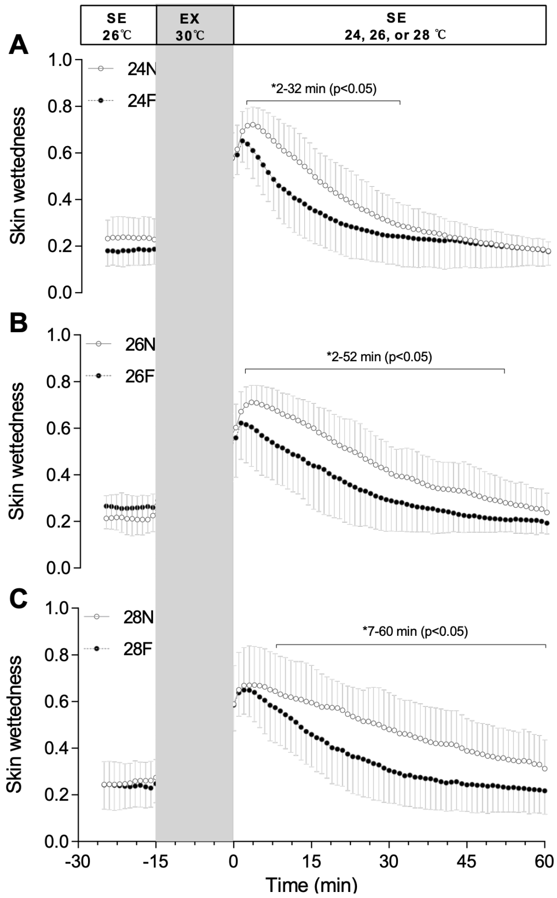

Fig. 13. Skin wettedness. Data show mean (Black – Fan, White – No fan). Error bars show SD. Asterisk (*) indicate significant differences between Fan and No fan.

Fig. 14 shows the skin blood flow rate. After exercise, SBF rapidly decline to pre exercise levels during the first 10 min after entering the cooler room C. No significant difference were found at any test temperatures with and without fans, indicating that personally controlled air movement wouldn't change the blood flow responses in the face of the metabolic rate and temperature down-steps.

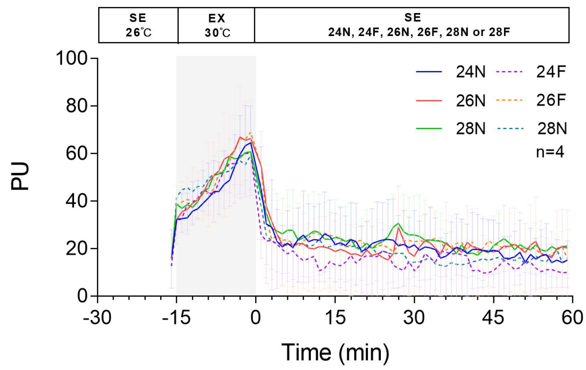

Fig. 14. Skin blood flow rate. Data show mean and SD.

4. DISCUSSION

How might a building design, or building operator, efficiently restore thermal comfort after exercise-induced thermal stress, such as commuting in hot summer? Our findings suggest that providing air movement is a more effective way to provide human thermal comfort during thermal and metabolic down-steps than providing a cooler air temperature. This overall conclusion is elaborated in the following points.

Air movement is seen to effectively relieve thermal discomfort after metabolic rate down-steps, even under warmer-than-typical room setpoint temperatures. It does this by enhancing the convective and evaporative cooling of the human skin (Figs. 11 and 12). It significantly shortened the time needed for TS, TC, and PD to return to comfortable values compared to still air at same temperatures. Air movement continued to improve comfort thereafter, especially at 28 °C, where significantly more subjects reached thermally neutral conditions than when they had no air movement. Our results confirm the positive effect of air movement at improving steady state comfort in warm temperatures [[16], [17], [18], [19], [20], [21]], while extending its usage into transition spaces where changes in metabolic rate and temperature may be experienced by the occupants at the same time. Air movement performed better than reducing room setpoint temperatures. We see that providing air movement at 26 and 28 °C delivered better TS, TC and PD recovery times than lowing ambient temperature to 24 °C (Table 4). Also, a very interesting result is that subjects were more comfortable with fans at both 26 and 28 °C than without fan at 24 °C over at least the first 30 min. Hence, air movement in the range of 0.5–1.0 m/s could offset 4 °C of ambient air cooling in spaces where people transition from outdoors to indoors. This supports the finding by Matsuzaki et al. [11] that the cooling effect of 25.8 °C with 0.5 m/s air speed exceeded that of 23.5 °C in still air (0.1 m/s air speed), after walking at 2.5 met in warm temperatures for 10 min. Mihara et al. [26] also suggested that comfort after walking in warm temperatures, cooling by ceiling fans could maintain the same level of comfort at 27 and 30 °C as 24 °C with the fan off. Our results are in line with these findings, while extending the positive effect of air movement to higher initial metabolic rates (4.4 met).

Table 4 Summary TS, TC, and PD recovery times *with* (F) and *without* (NF) fan

	24NF	26NF	28NF	24F	26F	28F
TS	13	19	>60	8	9	15
TC	15	21	40	6	6	9
PD	6	6	9	3	3	4

There is energy-saving potential in using air movement. As our results suggest, occupants are comfortable with air movement, in both transient and steady-state condition at 28 °C. Compared with other methods of environmental control such as reducing the air temperature or RH setpoints, maintaining a warmer setpoint (26 °C or 28 °C) would save roughly 20% and 40% cooling energy [[31], [32], [33]]. Our findings suggest important new solutions for environment control, especially for highly transient spaces such as building lobbies, subway stations, retail stores and shopping malls, and even office work spaces. A transitional space is a multi-functional space connecting the indoor and outdoor spaces of a building, and accounts for 10%–40% of the total area in various buildings [34,35]. In transitional spaces using relatively higher setpoint temperatures together with fans, people would reach their thermal comfort state faster with smaller energy expenditure.

Because fans so strongly establish comfort after metabolic down-steps over a broad range of temperatures, one might conclude that personal control of the fans during the transition period is not necessary. This would certainly be a beneficial conclusion for the practical control of air movement in lobbies, stores, etc. In this study people under a fan speed fixed for the maximum initial exposure would not become overcooled for 10–30 min, depending on the ambient temperature. This is a long residence time for transitional space. However, one might conclude from the large inter-individual differences in preferred air speeds in this study (Fig. 5) that destination spaces, such as offices where people are sedentary over extended periods, should offer personal control over cooling air flow. Subjects tended to reduce the air speed or even turn the fan off as they were cooled down, over periods in the 10's of minutes. This issue was seen in study [26] using a fixed ceiling fan speed, where the authors found that subjects' thermal sensation were in cool to slightly cool range (−1.87 to −0.77), rather than around neutral as in the current study.

It could be useful if air speed could be controlled automatically. Previously, target air speeds were established base on combinations of different temperature, relative humidity and metabolic rate, for steady-state sedentary [19,20] and elevated metabolic rates [23,24]. A similar approach employs a relation between metabolic rate (represented by heart rate because it is easier to measure using fitness trackers), ambient temperature, and preferred air speeds was established using the current data, as shown in Equation (4). It provides a simple equation for controlling ceiling fans where personal control is not available.

$$v = 0.033*HR + 0.058*T_a - 3.62\ (R^2=0.81) \quad (4)$$

Where

v preferred air speed, m/s

T_a temperature, °C, applies at 24-28 °C with 50% RH

HR Heart rate, bpm, as the indicator of metabolic rate

In temperature step changes, it has often been found that thermal sensation goes momentarily beyond the steady-state sensation for the second temperature condition, which is termed thermal sensation overshoot [36]. The current results show that after exercising (4.4 met) in the heat for 15 min, even with a temperature step up to 6 °C (30 °C→24 °C), no thermal sensation overshoot appeared. This was also the case in our previous study of a temperature down-step of 4 °C after exercising at 2.0, 3.0 and 4.4 met. It is likely that the overshoot perceived by sedentary subjects in down-steps of temperature alone is suppressed in our case by the concurrent decrease in metabolic rate.

It is worth noting limitations in the current study that might be addressed in the future. Humidity environments beyond the 50% RH tested here might produce variations in subjective sensations. Refs [8,9] suggested that the relative humidity affects people's comfort perception after exercise. Also, we used a climate chamber to simulate outdoor thermal condition, which could only control temperature and humidity, but not short-wave thermal radiation, such as people commuting under direct solar. A parametric study of the effects of temperature, humidity, direct solar, elevated air movement, and metabolic rate changes on transient human thermal comfort would be helpful for refining approaches to transient comfort control that are effective and energy-efficient.

Our previous study [3] found that although the metabolic level, heart rate, and skin blood flow were able to recover in a few minutes after the exercise and ambient temperature stepdown, the core temperature remained elevated during the entire 60 min. Further measurement of these longer-term heat storage changes after commutes would be useful in projecting occupants' thermal requirements over periods as long as a day.

In addition, age may also affect both thermal responses and preferred air movement after exercise. It was not possible here to explore the effects of age difference meaningfully. The current results apply mainly to young, healthy people. Subsequent studies might control for age and activity levels to better understand the comfort requirements for elder people.

5. CONCLUSION

Following physical exercise in the heat such as a commute in summer, people's skin temperature and skin wettedness are high. This study shows that personally controlled fans indoors provide an effective and fast way to remove excess body heat and moisture. Enhancing the convective and evaporative heat loss after exercise-induced thermal stress is more effective than reducing the ambient temperatures. Fans are seen to have restored subjects' baseline neutral sensations within 7–8 min after coming into the room whereas without the fan, it required 25, 40 and 60 min to reach the same levels, depending on the temperature.

Subjects were also more comfortable with air movement. With fans, 26 and 28 °C were more comfortable than 24 °C in still air, both during and after the 60 min transition period. This suggests improved design and summer operation of transition indoor spaces, in which air movement provides more effective comfort while saving energy through higher interior setpoint temperatures.

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REFERENCES

1. J. Pucher, J. Dill, S. Handy, S.M. Lee, J. F. Sallis, S. J. H. Biddle, Infrastructure, programs, and policies to increase bicycling: an international review. Preventive Medicine, 50(Suppl 1) (2010) S106-S125.
2. Y. Zhai, M. Li, S. Gao, L. Yang, H. Zhang, E. Arens, Y Gao, Indirect calorimetry on the metabolic rate of sitting, standing and walking office activities, Building and Environment, 145 (2018) 77-84.
3. Y. Zhai, S. Zhao, L. Yang, N. Wei, Q. Xu, H. Zhang, E. Arens, Transient human thermophysiological and comfort responses indoors after simulated summer commutes, Building and Environment. 157 (2019) 257–267.
4. G. Kenny, L.E. Dorman, P. Webb, M.B. DuCharme, D. Gagnon, F.D. Reardon, O. Jay, Heat balance and cumulative heat storage during intermittent bouts of exercise. Medicine and Science in Sports and Exercise, 41(3) (2009) 588–596.
5. B. Saltin, A P. Gagge, Sweating and body temperatures during exercise. International Journal of Biometeorology, 15(2) (1971) 189-94.
6. ANSI/ASHRAE/IES Standard 55-2013. Thermal environmental conditions for human occupancy. Atlanta, GA: American Society of Heating, Ventilation, Refrigerating and Air Conditioning Engineers. 2013.
7. ISO7730-2005. Ergonomics of the thermal environment–Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Organization for Standardisation, Geneva. 2005
8. K. Fukai. Experimental study on advantages of moderate temperature and low humidity air conditioning. Proceedings of Annual Meeting of Architecture Institute of Japan. (2000) 991-992. (in Japanese).

9. H. Tsutsumi, S. Tanabe, J. Harigaya, Y. Iguchi, G. Nakamura, Effect of humidity on human comfort and productivity after step changes from warm and humid environment. Building and Environment. 42 (2007) 4034-4042.
10. R. Tsuchiya, T. Ikaga, M. Miura, K. Harayama, K. Mizutani, S Ogawa. Proceedings of the 14th international conference of Indoor Air Quality and Climate, Ghent, Belgium, July 3-8 2016.
11. R. Matsuzaki, E. Miyake, Y. Miyashita, S. Tanabe. Optimum Indoor Thermal Comfort Conditions Required After Entering a Room from Outdoor Summer Heat. Proceedings of the 14th international conference of Indoor Air Quality and Climate, Ghent, Belgium, July 3-8 2016.
12. M. Sudo, S. Murakami, S. Kato, D. Song. Study on the Personal Air-conditioning System Considering Human Thermal Adaptation (Part7)-Thermal comfort and response time to thermal stimulus given from change of activity. The society of Heating, Air-Conditioning Sanitary Engineers of Japan, 2004. (in Japanese).
13. E. Bourdakis, A. Simone, B. W. Olesen, An experimental study of the effect of different starting room temperatures on occupant comfort in danish summer weather. Building and Environment 136 (2018) 269-278.
14. H. Zhang, E. Arens, Y. Zhai, A review of the corrective power of personal comfort systems in non-neutral ambient environments, Building and Environment. 91 (2015) 15–41.
15. J. Toftum. Air movement – good or bad? Indoor Air 14, (2004) 40–45.
16. Rohles FH, Woods JE, Nevins RG. The effect of air movement and temperature on the thermal sensations of sedentary man. ASHRAE Transactions 80(1) (1974) 01-19.
17. H. Kubo, N. Isoda, H. Enomoto-Koshimizu. Cooling effects of preferred air velocity in muggy conditions. Building and Environment 32(3) (1997) 211-218.
18. S. Schiavon, B. Yang, Y. Donner, V. Chang, W.W. Nazaroff, Thermal comfort, perceived air quality and cognitive performance when personally controlled air movement is used by tropically acclimatized persons, Indoor Air. 27(3) (2016) 1–23.
19. Y. Zhai, H. Zhang, Y. Zhang, W. Pasut, E. Arens, Q. Meng, Comfort under personally controlled air movement in warm and humid environments, Building and Environment. 65, (2013) 109–117.
20. Y. Zhai, Y. Zhang, H. Zhang, W. Pasut, E. Arens, Q. Meng, Human comfort and perceived air quality in warm and humid environments with ceiling fans, Building and Environment. 90 (2015) 178–185.
21. W Pasut, E Arens, H Zhang, Y Zhai. Enabling energy-efficient approaches to thermal comfort using room air motion. Building and Environment 79 (2014) 13-19.
22. B.W. Jones, K. Hsieh, M. Hashinaga, The effect of air velocity on thermal comfort at moderate activity levels. ASHRAE Transactions 92 (2B) (1986) 761-769
23. Y. Zhai, E. Arens, K. Elsworth, H. Zhang, Selecting air speeds for cooling at sedentary and non-sedentary office activity levels, Building and Environment. 122 (2017) 247–257.
24. Y. Zhai, C. Elsworth, E. Arens, H. Zhang, Y. Zhang, L. Zhao, Using air movement for comfort during moderate exercise, Building and Environment. 94 (2015) 344–352.
25. O. Jay, R. Hoelzl, J. Weets, N. Morris, T. English, L. Nybo, J. Niu, R. de Dear, A. Capon, Fanning as an alternative to air conditioning – A sustainable solution for reducing indoor occupational heat stress, Energy and Buildings. 193, (2019) 92–98.
26. K. Mihara, C. Sekhar, K.W. Tham, Y. Takemasa, B. Lasternas, Effects of temperature, air movement and initial metabolic rate on thermal sensation during transient state in the tropics, Building and Environment 155 (2019) 70-82.
27. ISO 8996: 2004. Ergonomics of the thermal environment - Determination of metabolic rate. International Organization for Standardisation, Geneva. 2004.
28. N. Ramanathan, A new weighting system for mean surface temperature of the human body, J. Appl. Physiol. 19 (3), (1964) 531–533.
29. F. Bauman, E. Arens, C. Huizenga, T. Xu, H. Zhang, T. Akimoto, K. Miura. The impact of humidity standards on energy efficient cooling in California. Final Report to CIEE. (1995) 11-12.
30. D. Kerslake. The stress of hot environment. Cambridge University Press, (1972) 38.
31. H. Zhang, E. Arens, D. Kim, E. Buchberger, F. Bauman, C. Huizenga, Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system, Building and Environment. 45 (2010) 29–39.
32. T. Hoyt, E. Arens, H. Zhang, Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. Building and Environment 88 (2015) 89-96.
33. S. Schiavon, A.K. Melikov, Energy saving and improved comfort by increased air movement, Energy and Buildings. 40 (2008) 1954–1960.
34. C. Chun, A. Tamura. Thermal comfort in urban transitional spaces. Building and Environment, 40(5) (2005) 633-639.
35. J. Tse, P. Jones, Evaluation of thermal comfort in building transitional spaces - Field studies in Cardiff, UK, Building and Environment, 156 (2019) 191-202.
36. A. Gagge, J. Stolwijk, J. Hardy, Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environmental Research, 1 (1967) 1-20