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Thermal comfort, perceived air quality and cognitive performance when personally controlled air movement is used by tropically acclimatized persons

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Abstract
In a warm and humid climate, increasing the temperature setpoint offers considerable energy benefits with low first costs. Elevated air movement generated by a personally controlled fan can compensate for the negative effects caused by an increased temperature setpoint. Fifty-six tropically acclimatized persons in common Singaporean office attire (0.7 clo) were exposed for 90 minutes to each of five conditions: 23, 26, and 29 °C and in the latter two cases with and without occupant controlled air movement. Relative humidity was maintained at 60%. We tested thermal comfort, perceived air quality, sick building syndrome symptoms and cognitive performance. We found that thermal comfort, perceived air quality, and sick building syndrome symptoms are equal or better at 26 °C and 29 °C than at the common setpoint of 23 °C if a personally controlled fan is available for use. The best cognitive performance (as indicated by task speed) was obtained at 26 °C; at 29 °C, the availability of an occupant-controlled fan partially mitigated the negative effect of the elevated temperature. The typical Singaporean indoor air temperature setpoint of 23 °C yielded the lowest cognitive performance. An elevated setpoint in air-conditioned buildings augmented with personally controlled fans might yield benefits for reduced energy use and improved indoor environmental quality in tropical climates.

Keywords Thermal comfort; Perceived air quality; Sick building syndrome; Cognitive performance; Air movement; Tropically acclimatized person

Practical Implications

Increasing the indoor temperature setpoint to values in the range 26-29 °C (79-84 °F) and simultaneously providing occupants with personally controlled fans could be a cost-effective, sustainable and energy-efficient option for providing thermal comfort in new and existing buildings in the tropics. We show that this strategy can be implemented without negative influence on the well-being of occupants, and with almost 100% thermal comfort satisfaction. Cognitive tests showed the lowest performance at 23 °C and the highest at 26 °C.

Introduction

Buildings are the locus of a significant portion of primary energy consumption. In Singapore, commercial and residential buildings are estimated to use 52% of electricity (EMA, 2014). Much of the energy is consumed to provide comfortable conditions indoors. Compression-based cooling can be a major contributor to total and peak load electricity use. Total energy use for cooling and its timing can have negative influences on energy cost, greenhouse gas emissions, and power grid reliability.

Overcooling during the warm season in the United States (Mendell and Mirer, 2009) and in tropical climates (de Dear and Fountain, 1994; Sekhar, 2016) simultaneously degrades thermal comfort and wastes energy (Derrible and Reeder, 2015). Overcooling is a dominant complaint in office buildings in Singapore; occupants prefer higher indoor temperature (Chen and Chang, 2012). Overcooling is a consequence of the need to guarantee proper dehumidification in HVAC systems that are oversized (Sekhar, 2005; Sekhar and Tan, 2009).

Personally controlled air movement can promote thermal comfort in warm environments (McIntyre, 1978; Tanabe and Kimura, 1989; Fountain et al., 1994; Zhai et al., 2013) and strongly reduce energy use (Sekhar, 1995; Schiavon and Melikov, 2008; Hoyt et al., 2015; Rim et al., 2015). In a warm environment, air movement is perceived as pleasant (Cândido et al., 2010), a feature that is aligned with the physiological principle of alliesthesia (Cabanac, 1971, 1979; de Dear, 2011; Parkinson and de Dear, 2015). Based on field studies in tropical climates, human thermal comfort can be maintained by natural winds and fan-generated airflow in naturally ventilated buildings (Cândido et al., 2010; de Dear et al., 1991). However, in thermal comfort standards, air movement is confined to a relatively low range to avoid draft risk (ISO, 2005). This limitation was recently removed from ANSI/ASHRAE Standard 55 (ANSI/ASHRAE, 2010). Elevated air movement has been proven to provide comfortable sleeping conditions in a warm and humid climate (Tsuzuki et al., 2008).

There is some risk that increasing temperature setpoints might result in a reduction of human cognitive ability (Seppänen and Fisk, 2006). However, if air movement is provided and the same thermal sensation is achieved, equal cognitive performance might be maintained (Lan et al., 2011). Air movement can compensate for higher temperatures with regard to thermal comfort and perceived air quality. On the other hand, laboratory experiments on 24 subjects showed that sick building syndrome (SBS) symptoms were not improved by elevated air movement (Melikov et al., 2013).

Previous studies showed that human thermal sensation was significantly improved by elevated air speed generated from different types of personally controlled fans under warm and humid conditions. However, these studies were limited in their sample size, the use of clothing level that was too light and a primary research focus on thermal comfort. The research described here assesses the merits of higher temperature setpoints along with user controlled air movement in a large sample size experiment for tropically acclimatized people who are dressed in typical Singaporean office attire in a room that resembles an office environment. In addition to thermal comfort, we assess perceived air quality, sick building syndrome symptoms, and cognitive performance.

Methods

Experimental Facilities and Instruments

The experiments were conducted during June-July 2014 in a room at Nanyang Technological University (Figure 1A and 1B). The room is normally used for class sections, workshops, and tutorials. The dimensions are 8.0 × 8.0 × 2.7 m (volume = 173 m^3). Two sets of ceiling mounted cassette type fan-coil units (Model FCQ50K, Daikin, Osaka, Japan) are used to control dry-bulb temperature. The humidity was controlled with two dehumidifiers (LD136FSD0, LG, Seoul, South Korea). The room has no window and one wooden door. The room is configured to simulate an open plan office without partitions. One workstation, marked as No. 1, accommodates four persons without fans. The other four workstations, marked as No. 2 to No. 5, accommodate one person each and include personal control of a fan. The central workstation, at which were situated the dehumidifiers and CO_2 meters, was occupied by the experimenter.

Personally controlled air movement was attained using three-phase brushless direct current (DC) fans. The axis of the fan blades and motor were at 1.1 m height, equal to the breathing zone of a seated person. Each fan consumes only 1.9 to 17.3 W for fan speed settings of 1 to 24, which generates airspeeds from 0.05 m/s to 2.5 m/s at 1 m distance and 0.05 m/s to 1.3 m/s at 2 m distance, respectively. For air temperatures of 26 °C and 29 °C, average fan speed settings for all subjects were 6.9 and 12.4 respectively. Corresponding fan power consumption was 4 W and 7.6 W, respectively. Technical details about the cooling fan, including its efficiency (Schiavon and Melikov, 2009) are described in Yang et al. (2015).

Dry-bulb temperature and RH were continuously measured at one-minute sampling intervals by HOBO temperature/RH/light data loggers (Model U12-012, Onset, Bourne, Massachusetts, USA), with -20 to 70 °C measuring range, ±0.35 °C uncertainty for dry-bulb temperature; and 5% to 95% measuring range, ±2.5% uncertainty for RH. Five HOBO U12-012 data loggers were located at 0.8 m height, one at each of the five workstations. Lighting intensity was measured but data are not used in this study. Carbon dioxide was monitored continuously at the central desk (Figure 1A) with a CO_2Meter (CM-0018, Ormond Beach, FL, USA) possessing an accuracy of ±30 ppm ±3% of the measured value in the range of 0-10,000 ppm. Two CO_2 meters were located at 0.8 m and 1.6 m height at the central workstation. All test instruments were calibrated before starting the experiments.

Experimental Conditions and Procedure

Experimental conditions are shown in Table 1. The baseline temperature of 23 °C is the typical setpoint in commercial buildings in Singapore (Sekhar, 2005). The other two conditions were selected based on previous research on the use of personally controlled fans (McIntyre, 1978; Zhai et al., 2013). Relative humidity was controlled at 60% for all cases, a typical indoor value in Singapore. In these experiments, we controlled dry-bulb air temperature because this is the most common way that the thermal environment of buildings is controlled in Singapore. An assessment performed before the tests showed that the dry-bulb air temperature was equal to the operative temperature. This result is obtained because the room has only one exterior wall, which was fully shaded, and it does not have windows. All subjects completed the sessions in the same order of temperature (26 °C, then 29 °C, then 23 °C).

The subjects were not made explicitly aware of the conditions tested except for the presence of the fans. The experimenter in the room was aware of the conditions (i.e., experimental conditions were single-blinded). Due to the time required for changing the temperature in the room, temperature was used in a block experimental design and people were assigned in random order to cases with and without fans. The background noise level in the room was 42 dB(A). The background noise was mainly generated by the dehumidifier, and fans in the computers and projectors. The personally controlled stand fans used for convective cooling made minor contributions to the background noise.

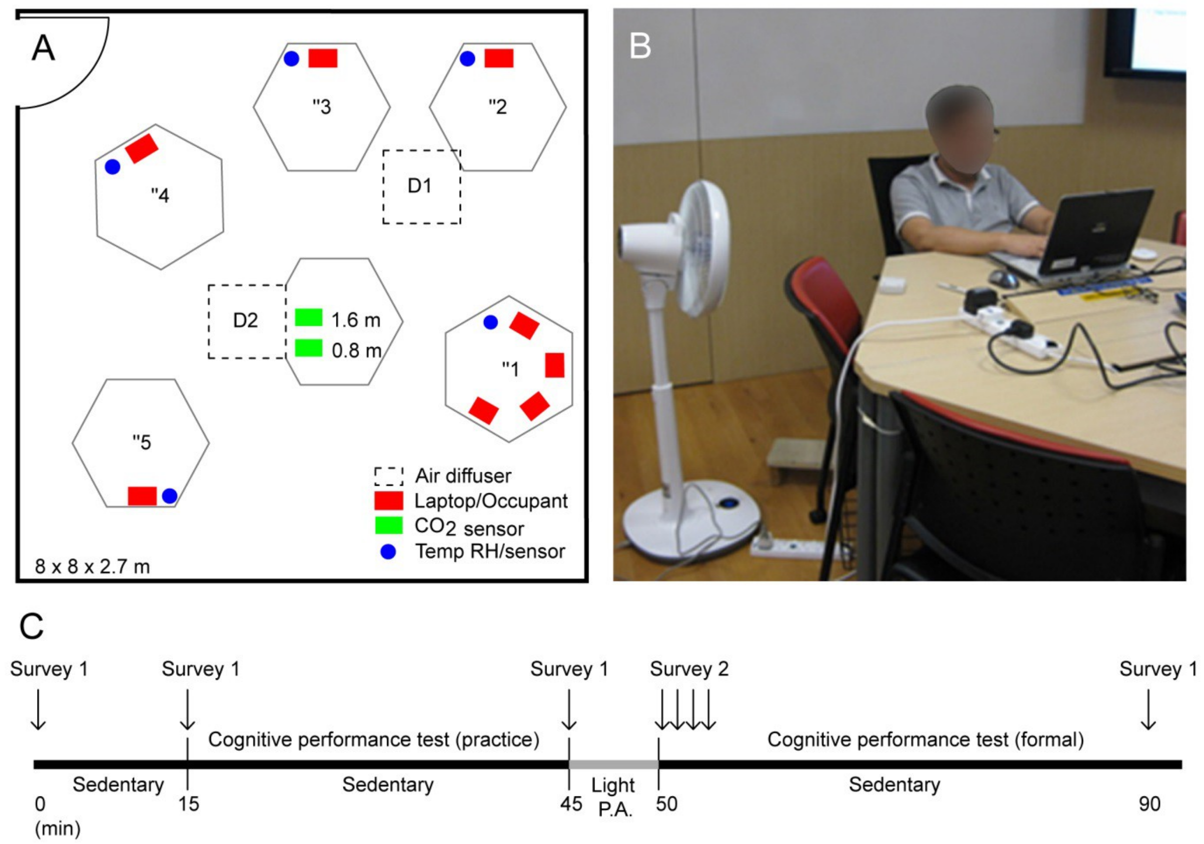

Fig 1 (A) Test room layout; (B) photo of one workstation equipped with stand fan; and (C) experimental procedure. (Note: P.A. = physical activity.)

Table 1 Experimental conditions

Experiment designation	Target dry-bulb air temperature (°C)	Measured dry-bulb air temperature (°C)	Target relative humidity (%)	Measured relative humidity (%)	Personal air movement
23 no fan	23	23.1 ± 0.1	60	57.9 ± 1.9	No
26 fan	26	25.8 ± 0.2	60	58.5 ± 2.5	Yes
26 no fan	26	25.8 ± 0.2	60	58.5 ± 2.5	No
29 fan	29	28.8 ± 0.1	60	62.3 ± 3.8	Yes
29 no fan	29	28.8 ± 0.1	60	62.3 ± 3.8	No

Before initiating formal experiments, the test room was conditioned to the dry-bulb temperature and RH according to Table 1 for at least one day. Steady state was maintained, with an 800 W heater to simulate heat generation from eight occupants. One stand fan was used to generate background air movement in the room. When the eight human subjects entered the room and the formal experiment was started, the 800 W heater was switched off.

Each experiment lasted 90 minutes (Figure 1C) to simulate normal office work with metabolic activity level of 1.1 met except during physical activity. One day before each experiment, subjects were required to practice cognitive performance tests at least three times to limit experimental uncertainty from the learning effect. Subjects were asked to arrive to the test room 15 minutes before the experiment started. When they had just entered the room and were seated, they were asked to fill in survey 1, with detailed questions regarding thermal comfort, perceived air quality and SBS symptoms. After 15 minutes, they were asked to fill in survey 1 again. Then they practiced the series of cognitive performance tests. After another 30 minutes, they filled in survey 1 for the third time. After that, subjects were asked to stand up and leave their workstations. They were asked to walk around, stretch arms and legs, and take 60 vertical steps with a 10 cm height step stool. Then they went back to their seats and answered survey 2 four times at 2-minute intervals. Survey 2 only has five questions regarding thermal sensation, and acceptability of thermal environment, humidity, air movement and air quality. After that, the subjects did the formal cognitive performance tests. At the end of the experiment, subjects were asked to fill in survey 1 for the fourth time before they left the room. During the whole experiment, subjects equipped with a fan were allowed to change fan speed and location. However, they were not allowed to use the mode in which the fan orientation oscillated.

Subjects

Subjects were students at the Nanyang Technological University. Table 2 reports anthropometric data. For all experiment conditions except one, there were 56 subjects. For the case at 23 °C, only 34 subjects participated owing to unanticipated logistical problems. The subjects were instructed to wear office attire that is typical of Singapore and other tropical climates: short sleeve button or polo shirt, long trousers, socks, and business shoes (0.55 clo). Each subject used the same type of business office chair with a cushion seat and mesh back (0.15 clo). Hence, the total clothing plus chair insulation was 0.7 clo. Subjects were allowed to lean forward or backward as in real offices but were not allowed to stand up or move around except as previously described. The protocols for all of these experiments were reviewed and approved by the NTU Institutional Review Board (IRB-2014-04-017). All subjects attended these experiments voluntarily and they were compensated for their time. Before attending formal experiments, all subjects attended one training session to become familiar with the experimental room, the experimental procedures, the attire requirements, the means of fan control, and the survey questionnaires. The subjects were instructed to eat normally before arrival at the lab and to have had enough sleep. Drugs and alcohol use were not allowed during the 24 hours prior to the experiment.

Questionnaire

Survey 1 includes ten parts: (1) thermal acceptability; (2) thermal comfort, thermal preference, and thermal sensation using the ASHRAE 7-point scale; (3) air movement acceptability, preference and perception; (4) humidity acceptability and sensation; (5) perceived air quality and air freshness; (6) dry eyes discomfort; (7) odor intensity symptoms; (8) eyes, nose and throat irritation; (9) feeling of sleepy/alert, bad/well, tired/rested; and (10) acceptability of noise generated by fan. Survey 2 includes five questions: (1) thermal acceptability; (2) thermal sensation; (3) air movement acceptability; (4) humidity acceptability; and (5) perceived air quality. The survey questions automatically appeared on the subjects' computer screen according to a preset schedule. The full questionnaire is shown in the Supporting Information.

Table 2 Anthropometric data (mean ± standard deviation) of human subjects

Gender	Sample size	Age (y)	Time in tropics (y)	Height (m)	Weight (kg)	BMI [a] (kg/m^2)
Male	28	25.7 ± 3.5	16.8 ± 11.6	1.74 ± 0.07	69.3 ± 10.3	22.8 ± 2.7
Female	28	23.7 ± 3.0	16.9 ± 9.2	1.62 ± 0.06	57.9 ± 10.5	22.1 ± 3.3
Total	56	24.7 ± 3.4	16.8 ± 10.4	1.68 ± 0.09	63.6 ± 11.8	22.5 ± 3.0

[a] Body mass index = weight (kg)/[height (m)]^2.

The ASHRAE seven-point scale varies between cold and hot, as follows: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (1), warm (2), hot (3). For this scale, subjects record their condition on a continuous scale. For acceptability, the subject marked his or her response on a continuous scale from clearly acceptable (+1) to acceptable (0.1) and from unacceptable (-0.1) to clearly unacceptable (-1). In this scale, subjects are compelled to distinguish between acceptable and unacceptable.

Cognitive Tests

Four cognitive tests were used, as described briefly below. The tests were chosen from well-studied and commonly used tasks to measure several cognitive skills, including processing speed, motor function and several executive functions (Diamond, 2013). All tests are related to general intelligence. Tests were taken on a computer, through the cognitive testing platform Quantified Mind (http://www.quantified-mind.com).

Test (1) — Choice Reaction Time (CRT) with three choices (Deary et al., 2001). This test measures processing speed and alertness.

Test (2) — Finger Tapping (FT) (Shimoyama et al., 1990). The subject is asked to tap the space bar as quickly as possible for 10 seconds on four separate trials. This test measures motor speed.

Test (3) — Stroop (ST) (MacLeod, 1991; Stroop, 1935). Three colors were used (red, green, blue). The subject is asked to type the first letter of either the word presented, or the color of that word. Example: for the word "green" displayed in red, the subject has to type "r" if the task is "Color", but "g" if the task is "Word". This test measures inhibition (the ability to suppress a learned response) and context switching (the ability to switch attention between different tasks), both relevant parameters of executive functions.

Test (4) — 2-Back (2B) (Owen et al., 2005). In each trial, one of four stimuli is displayed, and the subject is asked to press one key if the current stimulus is the same as the stimulus two trials earlier, and another key if it is different. This test measures working memory.

Scoring for CRT, ST and 2B was based on a simple deadline model (Ollman and Billington, 1972); for FT, the score was the rate of tapping.

Statistical Methods

The data distributions are reported using frequency box-plots. (The thick horizontal line is the median (M); the box bottom and top show the 25th and 75th percentiles, respectively. The vertical lines show the smaller of the extrema or 1.5 times the interquartile range of the data;

points beyond those lines are plotted as circles.) Numerical summary data are reported as medians with the 25th and 75th percentiles in parenthesis (e.g., 0.02 (-0.59, 0.54)).

Whether the data were normally distributed was tested with the Shapiro-Wilk normality test (Shapiro and Wilk, 1965). For non-normally distributed data, the Wilcoxon signed rank test was used (Siegel, 1956). For each case where a perfect pairing was possible (all except 23 °C and no fan), the paired option has been used. For normally distributed data the t-test and ANOVA were used. Correlations between variables were reported on the basis of Spearman's rank coefficient if the variables were not normally distributed and with the Pearson correlation coefficient if the variables were normally distributed. When needed, the effect size for binary variables was calculated with the mean square contingency coefficient (Cohen, 1992; Ferguson, 2009). To assess the cognitive data, principal component analysis (Jolliffe, 2002) and a linear mixed-model were used (Faraway, 2006). That fewer subjects participated in the 23 °C sessions was automatically handled by such models, since only observed data points were used for the optimization function that was employed for coefficient estimation.

For all tests, the results were considered statistically significant when $p < 0.05$. The statistical analysis was carried out using R software version 2.15.1 (R Development Core Team, 2015). Graphs were developed using GGplot2. Thermal comfort and perceived air quality results collected only at the end of the test (i.e., after 90-min exposure to a given condition) are reported in this paper.

Results and Discussion

Thermal Comfort

Thermal sensation votes (from -3 = cold to + 3 = hot) for the five tested conditions are shown in Figure 2A. Thermal sensation was normally distributed ($W = 0.99$, $p = 0.11$). The median value for the 23 °C case (without fan use) was -0.47 (1st quartile = -1.09, 3rd quartile = 0.03). Most of the occupants recorded their thermal sensation in the range neutral to slightly cool. When the dry bulb temperature was 26 °C, the median values of thermal sensation for cases with and without fans were -0.20 (-0.86, 0.02) and 0.24 (-0.05, 0.83), respectively. When the temperature was 26 °C, most of the subjects without a fan expressed that their thermal sensation was in the range neutral to slightly warm. With a fan, the thermal sensation votes were mainly in the range between neutral and slight cool, not statistically different ($p = 0.68$) than the case at 23 °C. It is noteworthy that the median value for 29 °C with a fan was -0.01 (-0.39, 0.33), which is effectively neutral. These results show that similar thermal sensation can be obtained at 26 °C ($p = 0.68$) and 29 °C ($p = 0.03$, where the difference is barely significant and favors the 29 °C condition) as at 23 °C if a personally controlled fan is provided. The case at 29 °C without a fan constituted a slightly warm environment, with a median thermal sensation of 0.89 (0.48, 1.24).

Thermal acceptability votes for the five tested conditions are shown in Figure 2B. Thermal acceptability is the most important parameter assessed because it is the foundation of thermal comfort standards: 80% or more of occupants should express satisfaction with the environment. In all cases except for 29 °C without fans, the thermal environment met the requirements of thermal comfort standards (ANSI/ASHRAE, 2013a; CEN, 2007; ISO, 2005). The highest satisfaction rate was obtained for cases with a user-controlled fan. In these cases, 100% at 26 °C and 98% at 29 °C of the subjects found the thermal environment acceptable. Removing the fan at 26 °C reduced the acceptability from 100% to 93%; four subjects were dissatisfied. At 23 °C (no fan), 85% of the subjects found the environment acceptable; five people were dissatisfied. These results show that higher acceptability can be obtained when people can use a personally controlled fan. A higher proportion of people found the thermal environment acceptable at 26 °C (with or without fans) than at 23 °C. Interestingly, thermal acceptability vote increased for cases without fans when temperature was increased from 23 °C to 26 °C , consistent with the concern about overcooling of air-conditioned buildings in tropical climates (Sekhar, 2016). Remarkably, when subjects were provided with a personally controlled fan, even 29 °C was acceptable to a higher proportion of subjects than was the case at 23 °C.

A slightly different result is obtained if, instead of looking at the data in a dichotomous way (acceptable and unacceptable), we use a continuous scale. Acceptability outcomes at 23 °C, 26 °C with fans and 29 °C with fans were statistically indistinguishable (p = 0.46 and p = 0.89, respectively). Each of these three cases was rated as superior to the two cases with higher temperatures and without fans.

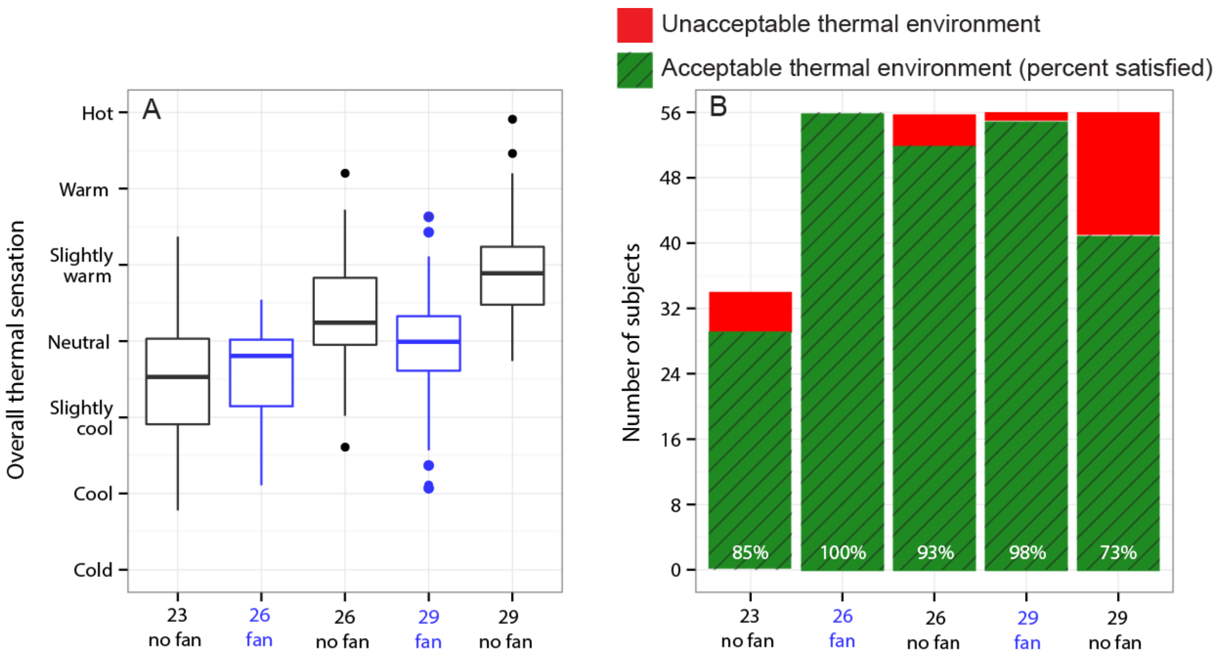

Fig 2 (A) Overall thermal sensation and (B) overall thermal acceptability for the five tested conditions. In blue are highlighted the cases with fans.

Thermal comfort votes (from -1 = very uncomfortable to 1 = very comfortable) for the five tested conditions are shown in Figure 3A. Thermal comfort was non-normally distributed (W = 0.96, $p < 0.001$). The highest rating of thermal comfort was achieved for the 26 °C case with fans. In this case, the median value was 0.74 (0.52, 0.88), not statistically distinguishable (p = 0.07) from the case at 23 °C without fans, for which the median value was 0.61 (0.32, 0.79). Effectively, the same thermal comfort (p = 0.71) was obtained at 23 °C as at 29 °C with fans. The median value 0.54 (0.34, 0.85) of the thermal comfort vote for the 29 °C case with a fan was higher ($p < 0.001$) than the median value 0.42 (0.20, 0.56) for 26 °C case without fans. Overall, the highest comfort is achieved for 23 °C without fans, and for 26 °C and 29 °C with fans.

Thermal preference votes for the five tested conditions are shown in Figure 3B. Thermal preference vote is important because it is the translation of the complex thermal state of an occupant into an actionable statement (i.e., “I want it warmer or cooler” or “I want no change”). Eighty percent of the subjects chose “no change” for the 26 °C case with fans, which was the highest value. Somewhat lower extents of expression for no change were obtained at 23 °C with no fan (68%) and for 29 °C with fans (66%). These results clearly show that subjects were least inclined to seek a change in the thermal environment at 26 °C with a fan, meaning that this condition is the one that may minimize thermal distraction.

Effectively equivalent conditions were created at 29 °C with fans and at 23 °C without fans. The personally controlled fan increased significantly the desire for no change both at 26 °C and 29 °C (from 46 to 80% and from 11 to 66% respectively). The 29 °C case without a fan is clearly outside of the thermal comfort zone, with 89% of the subjects wanting to be cooler.

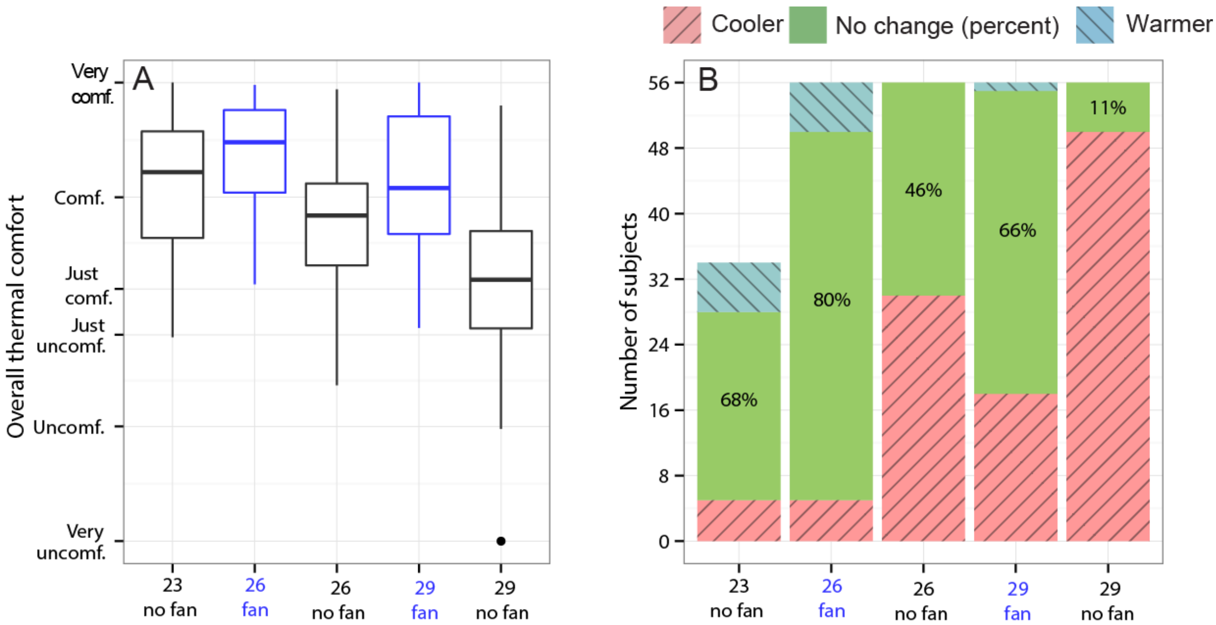

Fig 3 (A) Overall thermal comfort and (B) thermal preference ("Currently, you would prefer to be…") for the five tested conditions. In blue are highlighted the cases with fans.

Perceived Air Quality

Votes regarding the freshness of the air (perceived air quality) are shown in Figure 4A. Subjects answered the question "The air is…?" using a continuous scale from stuffy (-1) to fresh (1). Perceived air quality is non-normally distributed (W = 0.96, p < 0.001). For all cases, the air was perceived as close to fresh, except for 29 °C without fans. Without fans, the perceived air quality significantly declined from 0.41 (0.10, 0.70) through 0.27 (0.07, 0.61; p = 0.017) to 0.16 (-0.11, 0.51; p = 0.016), when the dry bulb temperature increased from 23 °C through 26 °C to 29 °C. Qualitatively, this result was expected (Fang et al., 1998). Perceived air quality tends to decrease with increasing air temperature. However, when occupant-controlled use of a fan was permitted, perceived air quality at 26 °C and 29 °C was statistically indistinguishable from the no-fan case at 23 °C. At 26 °C with a fan, the median perceived air quality vote is 0.61 (0.24, 0.79) (p = 0.85 comparing to 23 °C with no fan); corresponding values at 29 °C are 0.43 (0.13, 0.80) (p = 0.45). These results substantiate the positive effect of air movement on perceived air quality (Zhang et al., 2010; Melikov and Kaczmarczyk, 2012). The reasons of this effect are not yet established; a hypothesis has been described by Melikov and Kaczmarczyk (2012). Perceived air quality acceptability is shown in Figure 4B. As in the case of thermal acceptability, this is a key parameter because it is one of the measures of indoor air quality in standards (i.e., at least 80% of occupants need to express satisfaction with air quality). Acceptable indoor air quality according to ASHRAE 62.1-2013 (ANSI/ASHRAE, 2013b) is achieved for all cases except for 29 °C without fans. The highest satisfaction rating (94%) was obtained for the lowest temperature (23 °C). Without fans, the proportion of occupants who were satisfied declined from 94% through 80% to 62% with increasing dry-bulb air temperature from 23 through 26 to 29 °C. Adding user-controlled fans improved the perceived acceptability of air quality from 80% to 91% at 26 °C and from 62% to 88% at 29 °C. The results presented in Figure 4 show that suitably acceptable air quality and equally fresh air can be obtained at 26 °C and 29 °C as at the typical Singaporean temperature setpoint of 23 °C if personally controlled air movement is available.

We asked subjects to assess odor intensity on a scale between no odor and overwhelming. The odor intensity was strongly non-normally distributed (W = 0.88, p < 0.001). The median response for all the tests is between no odor and light and also all the medians for each test are between no odor to light odor. The use of the fan did not alter odor intensity to a statistically significant extent when the temperature was the same (p = 0.19 when temperature is 26 °C and p = 0.36 for 29 °C). There is not a clear effect of temperature. Odor intensity is slightly higher at 26 °C than at 23 °C (p = 0.016), but is the same at 23 °C and 29 °C (p = 0.09). Overall, the odor intensity is low, between no odor and light odor, and almost the same in all the tested conditions.

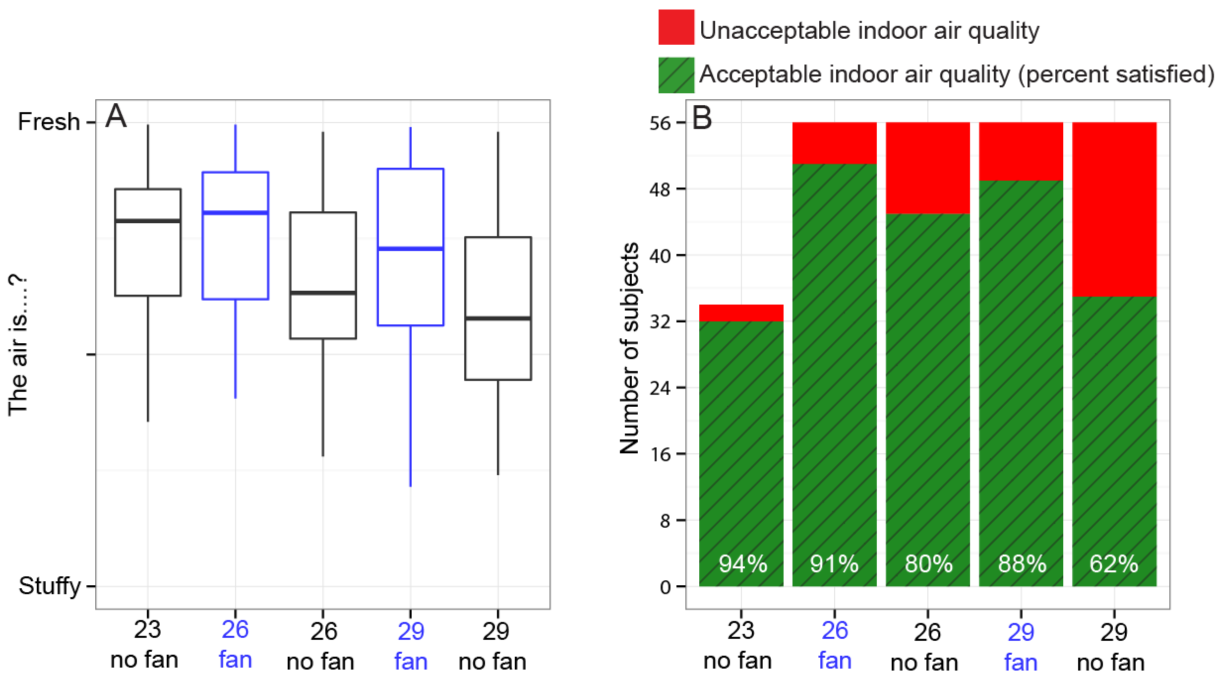

Fig 4 (A) Freshness of the air ("The air is…?" answer in a continuous scale from fresh to stuffy) and (B) perceived air quality acceptability for the five tested conditions.

Carbon dioxide was measured but not controlled during the experiments. The median CO_2 concentration was 1340 (1160, 1480) ppm. Taking into account the number of people in the room, and assuming a constant outdoor CO_2 concentration of 400 ppm and a constant CO_2 human emission rate of 34 g/h (0.31 L/min at 20 °C and 101.3 kPa), the ventilation air flow rate per person was 5.4 (4.8, 6.5) L/s. We did not measure the human emission rate; instead, we used the value suggested by ANSI/ASHRAE (2013b). A recent experiment with Chinese subjects showed that their emission rate could be smaller (Qi et al., 2014).

Carbon dioxide concentrations and ventilation rates for the different sessions are shown in Table S.1. The results are grouped based on temperature because in the same section some subjects used fans whereas others did not. Some data for 29 °C with/without fan were lost.

Under different room temperatures, median CO_2 concentrations and ventilation rates are summarized in Table 3. For the 26 °C case, the CO_2 concentration was slightly higher, indicating that the ventilation rate was slightly lower than in the other cases. The reason is unknown. To some extent, slightly elevated CO_2 concentration might interfere with the positive effect of fan use on perceived air quality and also enhance the negative effect of elevated dry-bulb air temperature on perceived air quality.

Table 3 Summary of measured CO_2 concentrations and inferred ventilation rates

Case	Median CO_2 concentration (ppm)	Median number of occupants	Ventilation rate (m^3/s)	Ventilation rate (L/s person)	Air-exchange rate (h^{-1})
23 °C	1030	8	0.06	7.8	1.3
26 °C	1450	9	0.05	5.0	0.9
29 °C	1220	9	0.06	6.3	1.2

Air Movement and Dry Eye

Air movement conditions were perceived to be slightly still when subjects did not have fans at 26 °C and 29 °C. Conversely, when subjects had fans, or when the temperature was 23 °C, air movement was perceived as just right (see Figure 5A). Indeed, at 23 °C, and at 26 °C and 29 °C with fans, more than 97% of the subjects were satisfied with air movement. The percentage decreased to 79% and 71% when the fan was not present at 26 °C and 29 °C, respectively (Figure 5B). When the temperature was high and people did not have access to a fan, 68% and 89% of the subjects wanted more air movement (see Figure 5D). These results show that when the room temperature is at 26 °C and 29 °C, people want to have air movement and, if it is under their control, they can select a speed that satisfies them.

Votes regarding discomfort from dry eyes are shown in Figure 5C. Dry eyes discomfort is non-normally distributed ($W = 0.92$, $p < 0.001$). For all cases, large majorities of subjects did not feel dry eye discomfort (88% at 23 °C, 93% at 26 °C with fan, 86% at 26 °C with no fan, 91% at 29 °C with fan, 89% at 29 °C with no fan). Eye comfort decreased with increasing temperature ($p < 0.001$). There was no significant difference between 23 °C and 26 °C with fans ($p = 0.20$), but eye comfort was significantly higher at 23 °C than at 29 °C with ($p = 0.048$) and without the fan ($p = 0.015$) and at 26 °C without the fan ($p = 0.043$). These results indicate that discomfort with dry eyes was not a major issue and that fan use did not influence its prevalence ($p = 0.82$). Increasing air temperature slightly decreased eye comfort. This result is consistent with previous short exposure studies on personal comfort systems (Zhang et al., 2010); however, the results contrast with other studies that have merged approaches from indoor air science, occupational health, and ophthalmology and found that high air speeds (above 1 m/s) and high temperature are risk factors for dry eye complaints (Wolkoff et al., 2005; Wyon and Wyon, 1987). Caution should be exercised in extrapolating from our findings because of the relative short exposure times and youthful subjects.

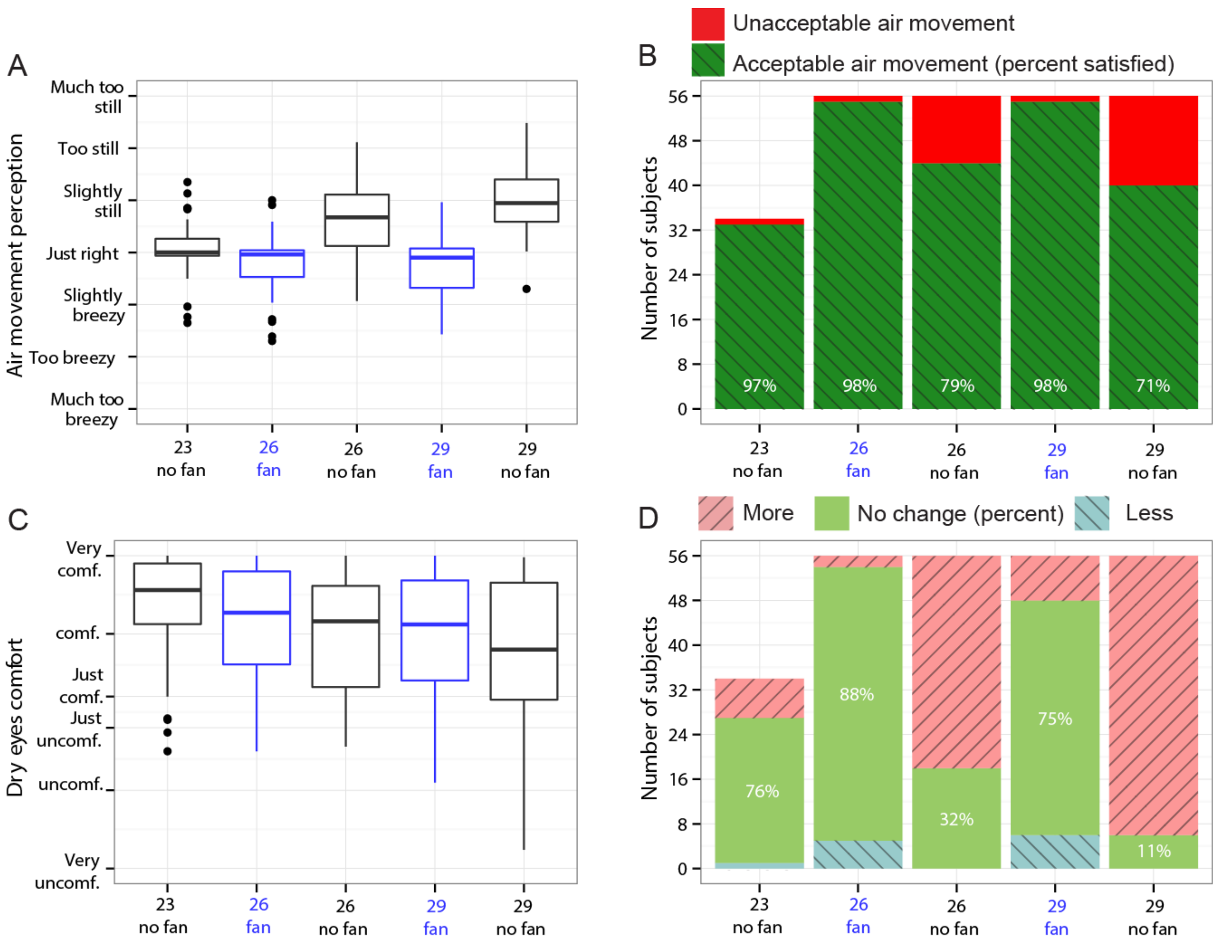

Fig 5 (A) Air movement perception; (B) air movement acceptability; (C) dry eyes comfort; and (D) air movement preference for the five tested conditions. In blue are highlighted the cases with fans.

At the end of each test, fan location, distance, and speed setting were recorded (Table S.2). At 26 °C with the fan and at 29 °C with the fan, the median distance was 0.8 (0.7, 0.9) m and 0.9 (0.7, 1) m, respectively. Air speed at target point (human facial area) was deduced based on previously collected data (Yang et al., 2015). Previous data were collected only at 1 m and 2 m. Assuming that the distance was 1 m, we roughly calculated that 26 °C with the fan and at 29 °C with the fan, the median air speeds were 0.9 (0.7, 1.2) m/s and 1.5 (1.3, 2.0) m/s, respectively. Worth highlighting here is that during the experiments the subjects were allowed to change the fan position and speed; therefore, the values reported above are just a snapshot of the distances and speeds used.

Humidity

In these experiments, relative humidity was maintained at 60%. With an increase of temperature, the absolute humidity increased. Of potential concern is that occupants would sense the more humid condition and find it unacceptable. We tested this possibility with two questions (humidity sensation and acceptability). The results are shown in Figure 6A and B. The humidity sensation is non-normally distributed ($W = 0.94$, $p < 0.001$).

In all experiments, subject felt neither dry nor humid: for all cases the humidity sensation was 0.1 (-0.02, 0.14)). For each case, the median was close to neutral. What changed was the spread of the data, becoming greater with increasing temperature and being reduced by the availability of fans. Subjects felt drier at 26 °C with no fan than at 23 °C ($p = 0.02$) or than at 29 °C with fans ($p < 0.001$). All other conditions were not significantly different. Humidity acceptability (Figure 6B) was the same at 23 °C and 26 °C with and without the fan (higher than 97%). Acceptability decreased at 29 °C, in particular when there was no fan available (acceptability was 93% with fans and 80% without fans). These results show that increasing the temperature setpoint to 26 °C did not affect humidity acceptability. Increasing it to 29 °C did generate lower acceptability, and elevated air movement only partially mitigated this effect. Overall, from these results, we can conclude that increasing air temperature did not make subjects feel the environment to be more humid, but at 29 °C the acceptability was reduced compared to the values at 23 °C and 26 °C. Zhai et al. (2013) found that, when relative humidity was 60%, perceived humidity was acceptable at 28 °C but not at 30 °C. For tropical environments, where dehumidification is a chronic need, this evidence suggests that 29 °C might be the maximum acceptable limit for occupants who are provided personal control over a fan.

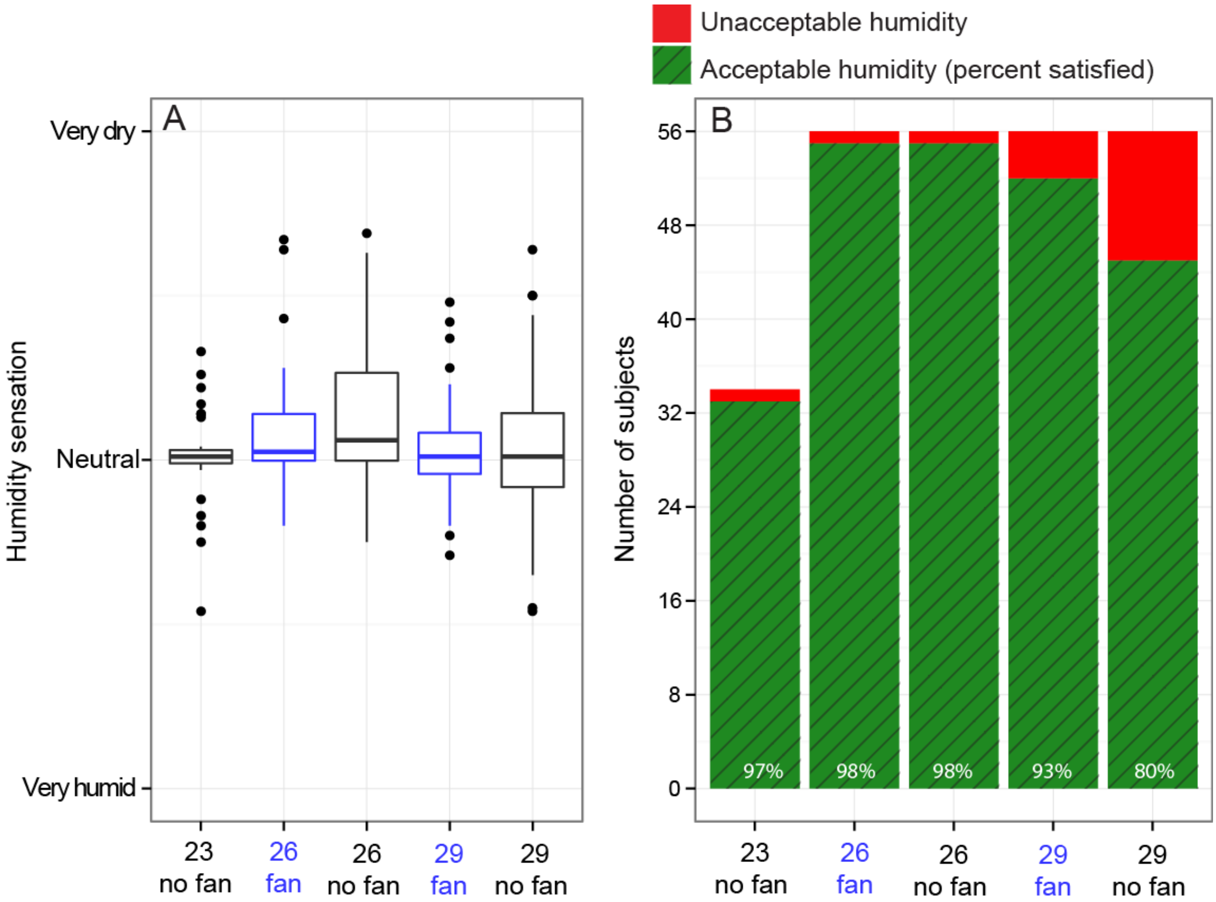

Fig 6 (A) Humidity sensation and (B) humidity acceptability for the five tested conditions. In blue are highlighted the cases with fans.

Fan Noise Acceptability

We asked subjects to rate the acceptability of the noise generated by the fans. Among the participants, 93% (241 out of 258) found the noise acceptable, and the noise acceptability was 0.63 (0.22; 0.91) in a scale from -1 to 1. Almost all (97%) of the subjects that had control of a fan found the noise acceptable (0.71 (0.42, 0.92). If they did not have control, the acceptability decreased to 90% (0.52 (0.15, 0.84)). The fans tested in this study were not an important source of noise and acceptability of the noise increased when people had personal control.

Sick Building Syndrome Symptoms

We asked subject to rate their level of irritation in eyes, nose, and throat using a continuous scale from no (-1) to overwhelming (1). For all these parameters the data were non-normally distributed (W = 0.85, W = 0.79, W = 0.78, p < 0.001 for all the tests). The results are shown in Figure 7. Median irritation was always between no and light for eyes, nose, and throat. Eye irritation (-0.79 (-0.93,-0.50)) was slightly higher (stronger) than nose irritation (-0.85 (-0.96, -0.55)) and throat irritation (-0.86 (-0.96,-0.59)). Using a fan and increasing the setpoint temperature did not affect nose irritation (p = 0.95 for fan, p > 0.33 for all temperature combinations) or throat irritation (p = 0.88 for fan, p > 0.26 for all temperature combinations). Using a fan did not affect eye irritation (p = 0.22). Eye irritation at 23 °C was significantly lower than at 26 °C without fans (p = 0.027) and lower to an almost significant level at 26 °C with fans (p = 0.051). For all other combinations, the difference was not statistically significant. Overall, we found that, during the experiments, the subjects did not suffer from eye, nose and throat irritation and the increase of the temperature setpoint and the use of the fan did not significantly influence irritation. It is possible that with longer exposure, the use of fans and the elevated temperature might lead to eye irritation.

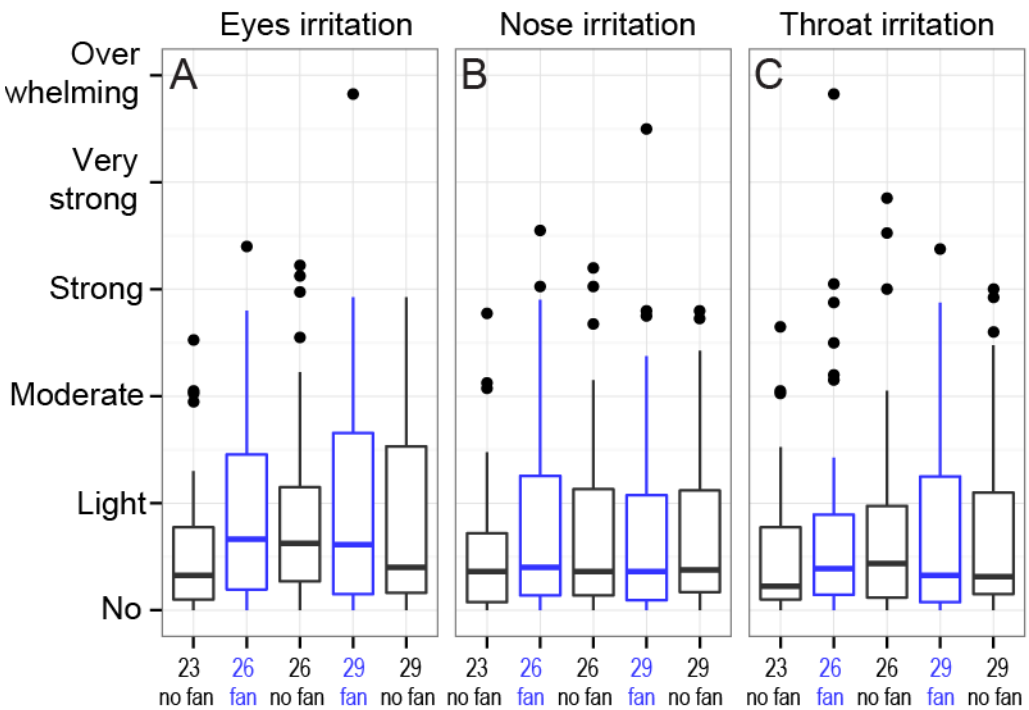

Fig 7 Rated irritation for the five tested conditions for (A) eyes, (B) nose and (C) throat. In blue are highlighted the cases with fans.

We asked subjects to report how they were feeling using continuous (-1, 1) scales for several indicators: (A) alert to sleepy; (B) well to bad; and (C) rested to tired. For each of these parameters the data are non-normally distributed (W = 0.94, W = 0.92, W = 0.93, p < 0.001). The results are shown in Figure 8. Overall, people reported feeling alert (-0.33 (-0.72, 0.17)), well (-0.54 (-0.83, -0.07)), and rested (-0.37 (-0.72, 0.14)). Responses to the three questions were moderately correlated: the Spearman rho coefficients varied from 0.67 to 0.79; $p < 0.001$ for each case.

Subjects reported feeling statistically more alert at 23 °C than at 26 °C with a fan (p = 0.006) and without ($p < 0.001$) and at 29 °C (p = 0.003) without a fan. The difference between 23 °C and 29 °C with a fan was not statistically significant (p = 0.08).

People reported feeling statistically better with a fan than without it at each of the two temperatures tested (at 26 °C, p = 0.027; and at 29 °C, $p < 0.001$). Differences in response to the well/bad question were not statistically different at 23 °C as compared with 26 °C (p = 0.22) and 29 °C (p = 0.45) if a fan was available. Increased temperatures without a fan had people feeling worse (at 26 °C, p = 0.01; at 29 °C, p = 0.006).

People reported feeling more rested with a fan than without it at each tested temperature (at 26 °C, p = 0.05 and at 29 °C, p = 0.005). Differences in response to the rested/tired question were not statistically different at 23 °C as compared with 26 °C (p = 0.06) and 29 °C (p = 0.31) if a fan was provided. Increasing the temperature without providing a fan did have subjects reporting that they felt more tired (at 26 °C, $p < 0.001$; and at 29 °C, p = 0.004).

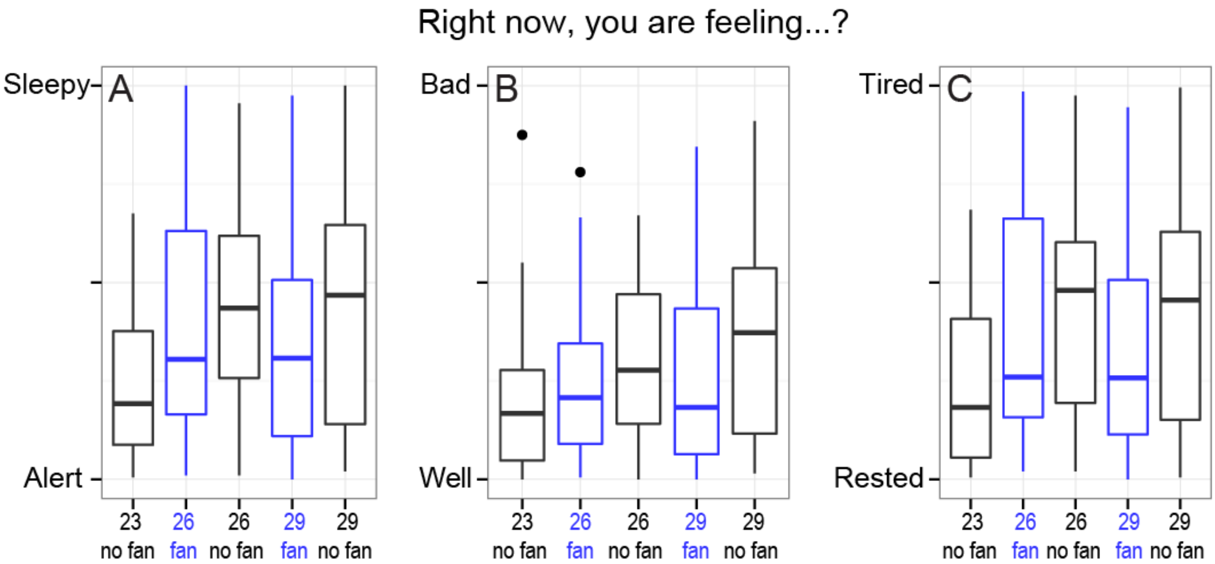

Fig 8 Feeling of (A) alert/sleepy; (B) well/bad; and (C) tired/rested. In blue are highlighted the cases with fans.

Overall one can conclude that increasing the temperature setpoint alone, from 23 °C to 26 °C or 29 °C, has a detrimental effect: people feel sleepier, less well and more tired. However, if a personally controlled fan is provided, people reported that they felt effectively the same at the three temperatures, or at least any reported differences did not rise to a level of statistical significance except in the case of the alert/sleepy question.

This outcome is different than what was reported by Melikov et al. (2013). In that study, the response of 24 human subjects to local convective cooling at 28 °C and 50% relative humidity was tested for four different cooling devices (two of them were a desk fan and a personal ventilation system). The researchers found that air movement significantly improved subjects' report of thermal acceptability and perceived air quality compared to the condition without it. But, they also found that air movement had little effect on sick building syndrome symptoms. In the present study, we found that the fan was effective in reducing SBS symptoms. A feasible explanation, although not confirmable, is that the room used in this experiment had a lower pollution load than the one used by Melikov et al.

Cognitive Performance

Results of different cognitive tests are positively correlated and are related to a general intelligence factor, also referred to as IQ or *g* factor (Jensen, 1998). General intelligence is a construct used to assess cognitive abilities and principal component analysis (PCA) is a standard approach to quantify it in a battery of cognitive tests. PCA analysis revealed a main general intelligence component that accounted for 76% of the variance on all four tests. This means that all the tests used in this study are positively correlated with general intelligence and this outcome supports a view that they are valid for measuring aspects of general intelligence. PCA results also revealed a second component that accounted for 17% of the variance separating the two executive tasks from the two speed tasks. Based on the PCA results, we created three compound scores: 1. "*g*": the average of all four tasks. 2. "*Exec*": the average of ST and 2B. 3. "*Speed*": the average of CRT and FT.

We expected that the executive function tests but not the speed tests would show strong practice effects. To assess practice effects, we fit linear mixed-effect models with random effects for subject and condition and fixed effects for amount of previous practice. It is possible to assess practice effects independently of conditions because subjects completed multiple sessions under the same condition. As expected, both executive function tests (ST ($\chi^2(5) = 6.91$, $p = 0.008$); 2B ($\chi^2(5) = 10.55$, $p = 0.001$)) and the "*Exec*" factor ($\chi^2(5) = 7.24$, $p = 0.007$) show significant practice effects, but neither of the speed tests (CRT ($\chi^2(5) = 0.13$, $p = 0.72$); FT ($\chi^2(5) = 0.25$, $p = 0.62$)) or the "*Speed*" factor ($\chi^2(5) = 1.42$, $p = 0.23$) did. The general intelligence, "*g*" factor, did not exhibit a significant practice effect ($\chi^2(5) = 2.59$, $p = 0.11$).

Table 4 Effects of temperature on the speed tests [a, b]

Test	$\chi^2(5)$	*p*-value	Effect size [CI] for 23 °C	Effect size [CI] for 26 °C	Effect size [CI] for 29 °C
CRT	55.5	<0.001	-0.40 [-0.67,-0.12]	0.41 [0.19,0.62]	0.01 [-0.21,0.23]
FT	3.25	0.20	-0.09 [-0.38,0.21]	0.24 [0.12,0.35]	0.04 [-0.2,0.28]
Speed	45.5	<0.001	-0.25 [-0.47,-0.02]	0.26 [0.07,0.45]	0.02 [-0.17,0.21]

[a] CI: 95% confidence intervals

[b] Statistically significant results are reported in bold (p < 0.05)

All subjects completed the sessions in the same order of temperature (first 26 °C, then 29 °C, and then 23 °C). Therefore, temperature and practice are confounded. Although the average magnitude of the practice effect over all participants could be estimated due to multiple sessions per condition, on an individual level it was not possible to disentangle practice and temperature. Therefore, we cannot use the data related to executive function tests to assess the effects of temperature. Since the speed tests did not show practice effects, we could analyze the effect of temperature on these results. The effects of temperature on different aspects of cognition are likely to vary, so our results only apply to the speed domain. Table 4 shows the effects of temperature on the speed tests. For choice reaction time (CRT), the effect sizes were -0.40, 0.41 and 0.01 for 23, 26 and 29 °C (confidence intervals: [-0.67,-0.12], [0.19,0.62], [-0.21,0.22]). This outcome shows that subjects had the highest performance at 26 °C and that performance was better at 29 °C than at 23 °C. Increasing the temperature setpoint from 23 to 26 °C increased CRT (a measure of processing speed and alertness) by 0.81 standard deviation.

Table 5 Effects of using fans on all four cognitive tests and their constructs for the two temperature settings (26 °C and 29 °C)[a]

Test	Temperature (°C)	$\chi^2(4)$	p-value	Effect size [CI]
CRT	26	0.33	0.57	-0.04 [-0.18, 0.1]
CRT	29	0.90	0.34	0.08 [-0.09, 0.26]
FT	26	1.90	0.17	-0.10 [-0.25, 0.05]
FT	29	2.25	0.13	0.17 [-0.05, 0.39]
ST	26	2.35	0.12	-0.10 [-0.23, 0.03]
ST	29	0.80	0.37	0.06 [-0.07, 0.19]
2B	26	0.48	0.49	-0.05 [-0.19, 0.09]
2B	29	1.43	0.23	0.05 [-0.03, 0.13]
Speed	26	1.57	0.21	-0.07 [-0.19, 0.04]
Speed	**29**	**4.78**	**0.029**	**0.13 [0.01, 0.25]**
Exec	26	2.02	0.15	-0.07 [-0.17, 0.03]
Exec	29	1.93	0.16	0.06 [-0.03, 0.14]
g	26	2.70	0.10	-0.07 [-0.16, 0.01]
g	**29**	**6.12**	**0.013**	**0.10 [0.02, 0.17]**

[a] Statistically significant results are reported in bold ($p < 0.05$)

The ability to use a fan was fully randomized within the temperature settings; therefore, one can assess its effect on all four tests and their combinations. We analyzed the effect of fan separately for each temperature (26 °C and 29 °C). The results are shown in Table 5. At 26 °C, the fan did not have an effect. At 29 °C, using a fan provided a statistically significant positive effect for the "*Speed*" and "*g*" factors. The fan effect size was smaller than the performance decrease at 29 °C relative to 26 °C (compare entries in Tables 4 and 5).

One can conclude that, on average, the best speed-associated cognitive performance results were obtained at 26 °C and at this temperature having a fan did not improve performance. Increasing the temperature to 29 °C reduced the speed performance and having a fan only partially compensated. The typical Singaporean indoor air temperature setpoint of 23 °C was associated with the lowest cognitive performance associated with task speed.

An inverted-U relationship has been proposed to show the influence of moderate differences thermal environments on cognitive performance (Griffiths and Boyce, 1971;

Kosonen and Tan, 2004; Jensen et al., 2009; Lan et al., 2011). The inverted-U relationship is based on the Yerkes and Dodson's law (Yerkes and Dodson, 1908) and it is characterized by a unique optimal condition. This law has been criticized and an extended-U shape has been proposed (Hancock and Warm, 1989; Hancock and Ganey, 2003). Based on analysis of 26 studies, an inverted-U relationship between performance and temperature was developed (Seppänen and Fisk, 2006). They found that the temperature that would maximize performance is 21.6 °C and that performance indicators are reduced for any increment of temperature above 23 °C. At 26 °C the performance would be reduced by 3-4%; at 29 °C, the reduction would be 7-8%. These results from Seppänen and Fisk (2006) contradict previous results summarized in ANSI/ASHRAE Handbook-Fundamentals (ANSI/ASHRAE, 2013c). Our findings reported in this paper also did not obtain lower performance at 26 °C. Another study in Singapore (Tham and Willem, 2010) found that people performed cognitive tests faster with fewer errors at 26 °C than at 23 °C, an outcome that is similar to our findings even if the interpretation was different. The work of Zhang and de Dear (2016) contradicts the inverted-U shape with one optimal temperature. It is reasonable to assume that performance, like comfort and acceptability, does not depend on temperature alone. Cognitive performances are a construct with multiple dimensions. Therefore, a reductionist approach to compare performance with a single independent variable may not yield consistent results. It is possible that an integral measure of occupant satisfaction with the indoor environment — such as thermal sensation, preference or thermal satisfaction (Tanabe et al., 2015) — could be a better predictor of productivity.

Limitations

This study used a relatively large sample size as compared with typical thermal comfort research. On the other hand, all subjects were young college students. However, there are no known or expected significant differences in preferred thermal conditions between college students and office workers (Collins et al., 1981; Fanger and Langkilde, 1975; Rohles and Johnson, 1972). The results of the present study have been obtained for tropically acclimatized subjects and the results should be applied with caution to people acclimated to other conditions. Different results may be obtained using different fans. As shown in Figure 1, the subjects with the fan had a relative large distance among them, whereas the subjects without the fan were grouped at one table. This fact may give rise to two possible problems for the subjects without the fan: (a) proximity discomfort and (b) higher mean radiant temperature. Being forced to stay close to other people may create discomfort and anxiety. The minimum amount of personal space depends on cultural, personal and environmental factors. Given that the experiments were performed on young college students living in highly dense urban environment, we assumed that this issue would not have a large effect. Mean radiant temperature for subjects without fans may be slightly higher than subjects with fans because of the relatively high occupant density. This effect should be relatively small compared to the uncertainty related to clothing insulation and metabolic activity estimation (Alfano et al., 2011).

Exposure time was 90 min, a long time for thermal comfort studies, but shorter than the typical work day duration for real office workers. It is possible that, in the short term, persons react in a way that the effect of the environmental stress on performance is not evident. Such effects may emerge after longer exposures.

Owing to practical physical constraints, the order of presentation of temperature exposures was not randomized in this study. For the cognitive tests involving executive function, a learning effect was observed. Owing to this limitation in the design of the experiments, we were not able to use tests related to executive functions to investigate the possible effects of increased temperature setpoints.

Conclusions

A typical temperature setpoint in Singaporean commercial building is 23 °C. Increasing temperature setpoint could yield substantial net energy savings, have low cost for implementation in existing buildings and offer first-cost reductions in new buildings. We performed a large sample-size experiment for tropically acclimatized people who are dressed in typical Singaporean office attire in a room that resembles an office environment. We assessed thermal comfort, perceived air quality, sick building syndrome symptoms and cognitive performance. We studied five conditions for the thermal environment: 23, 26, and 29 °C and in the latter two cases with and without occupant controlled air movement.

We found that thermal comfort and perceived air quality were equal or better at 26 °C and 29 °C than at 23 °C if a personally controlled fan was provided. Therefore, mandating and maintaining the indoor temperature at 23 °C does not provide a more thermally comfortable environment as compared to 26 °C and 29 °C when people have access to a fan. A higher proportion of people found the thermal environment acceptable at 26 °C (whether with or without the fan) than at 23 °C. Remarkably, if they have a personally controlled fan, even 29 °C was acceptable to a higher percentage of subjects than was the case at 23 °C. Increasing the air temperature setpoint to 26 °C and 29 °C did not affect odor intensity perception and did not make the subjects feel the environment to be more humid. However, at 29 °C, the acceptability of perceived humidity was reduced compared to 23 °C and 26 °C.

We found that subjects did not suffer from eye, nose, and throat irritation in the studied setting. The increase of the temperature setpoint and the use of fans did not have a significant influence on irritation. If they did not have a fan, subjects felt sleepier, less well and more tired at 26 °C and 29 °C compared to 23 °C. However, if a personally controlled fan was provided, differences in how people felt at the three temperatures were not statistically significant except in the case of the alert/sleepy question.

We assessed speed as one attribute of cognitive performance. We found that the best cognitive performance results were obtained at 26 °C and at this temperature having a fan did not improve performance. Increasing the temperature to 29 °C reduced performance on tests of speed and having a fan partially mitigated this issue. The typical Singaporean indoor air temperature setpoint of 23 °C yielded the lowest performance.

Overall, for a tropical climate like Singapore's, increasing the temperature setpoint provides high energy saving potential with neutral or positive consequences on thermal comfort, perceived air quality, noise, well-being, sick building syndrome symptoms and cognitive performance. The evidence in this study does not support continued use of a temperature setpoint of 23 °C; instead, it does support the increase of the setpoint to at least 26 °C.

With further development on how to implement personally controlled air movement in practice and with more human subject tests utilizing longer periods of exposure (e.g., an 8-hour workday with appropriate breaks), the findings reported here could contribute to important changes in the way indoor air in tropical climates is conditioned.

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