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Thermal comfort and self-reported productivity in an office with ceiling fans in the tropics

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ABSTRACT

Here we present a field study examining the impact of elevated room temperature and air movement on thermal comfort and self-reported productivity. This experiment was performed in three environmental conditions (one with a set-point of 23 °C—a typical set-point used in Singapore—and two elevated (up to 28 °C) room temperature conditions). Occupants had shared control of ceiling fans.

The results show that the most comfortable thermal condition, with thermal sensation closest to neutral, is achieved at a room temperature of 26 °C with operating fans. Increasing the temperature set-point from 23 °C to 26 °C resulted in a significant increase in thermal acceptability (from 59% to 91%), and a 44 kWh/m^{2}yr savings in electrical energy used for comfort cooling. We found that a room's set-point temperature can be increased up to 27 °C without creating a negative impact when controllable air movement is provided compared to an environment with a set-point of 23 °C. Thermal satisfaction is significantly higher in spaces of 26 °C with operating fans, than when the room's temperature is set at the typical 23 °C. Moreover, the relative humidity in the office is decreased from 62% (when the temperature was 23 °C) to 50% when the temperature was 27 °C.

Occupant's self-reported ability to concentrate, be alert, and ability to be productive was comparably high in all conditions. The results indicate that work performance is poorly correlated with room temperature, but increases with greater individual thermal satisfaction.

1. Introduction

Extensive environmental field studies in tropical climates show that most commercial buildings are overcooled [1]. Overcooling not only results in high occupant dissatisfaction, but also in energy waste. Leading causes of this issue are oversized air handling units, which have limited ability to adapt to heat source changes, and dehumidification with supply air [1,2].

Compared to full refrigeration based air-conditioning strategies, an increase in the temperature set-point in hot and humid climates, together with elevated air movement, is a promising solution for increasing occupants' thermal satisfaction and bringing substantial energy savings. Energy simulation analyses of these solutions show projected savings up to 30% [3–6]. Laboratory studies show that elevated air movement at room temperature of 26 °C and above can increase the acceptability of thermal conditions up to 90–100% [7,8]. Thermal comfort in laboratory conditions can be achieved by increased air speed even at the room air temperature of 32 °C and relative humidity of 60% [9–12]. Similar results have been replicated in naturally ventilated buildings with ceiling fans in Brazil [13]. However, to our best knowledge, a field study examining elevated room temperature and air movement provided by ceiling fans in an actual office environment has not been conducted yet. Air movement also appears to compensate the adverse impact of increased temperature on occupants' perceived air quality and cognitive performance [7,12,14,15]. Moreover, results from field surveys show that about 60% of occupants feel as though air movement enhances their ability to work, while about 15% of occupants report that air movement interferes with their work performance [16].

Ceiling fans are both cost-effective and easy to implement (in both new and retrofit environments). Further, fans with direct current (DC) motors have up to 65% higher energy efficiency than alternating current (AC) fans. For standing fans, a change in motors can result in up to three times higher cooling efficiency [17]. Even more, DC motors allow for a wider range of fan speed set-points and emit less noise. Despite these advantages, ceiling fans are most predominantly used within the residential sector. However, several studies have suggested the need for air movement in office spaces. For instance, cross-study analyses of

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ASHRAE field studies and climatic chambers studies examined when air movement is perceived as most desirable and undesirable, and summarized the factors influencing those perceptions [10]. Exploration of other databases, Center for the Built Environment's Occupant Indoor Environmental Quality (IEQ) survey database [16] and ASHRAE RP-1161 dataset [18], has also yielded useful insights into these issues. These extensive datasets indicate that twice as many people prefer more air movement as opposed to it—even when occupants report experiencing cooler thermal sensations. These findings suggest that most air movement tends to be too low in workspaces—forcing occupants to seek personal remedies (such as opening a window or using a personal fan) to increase thermal comfort.

To analyze demand for air movement in warm environments, a series of survey studies were conducted in China [9]. Results showed that 78% of participants frequently use fans at home, even though 68% of those respondents also have installed air-conditioning. Additionally, 70% of respondents report that fans are an acceptable solution for offices. Interestingly, results also highlighted that the main advantages of ceiling fans in the office environment are: an increase in perceived air freshness, increased personal control, prevention of drowsiness, and a lack of risk of overcooling—as can happen with air-conditioning.

In response to findings like those mentioned above, both EN 15251 [19] and ASHRAE 55 [20] standards allow for an increase in a space's temperature with the presence of elevated air movement—even though each standard uses different calculation methods. For instance, according to EN 15251 [19], air velocity can be increased to 0.8 m/s which would compensate for an operative temperature increase by 2.8 °C above comfort temperature at still air. ASHRAE 55 [20] and EN ISO 7730 [21] extend the acceptable range of air velocity with regards to relative differences between both mean radiant and air temperature. Additionally, ASHRAE 55 [20] gives no air speed limit if occupants have the ability to personally control their thermal environment, or if the metabolic rate is above 1.3 met. The current Singaporean standard SS 553 [22] allows for an increase in operative temperature up to 26 °C when an air-conditioning system is in operation, but it also suggests that air movement should be limited to 0.3 m/s.

Previous studies examining increased temperature set-points and air movement have been performed in laboratory conditions. These types of studies tend to be conducted with short time exposure and are limited to simulated tasks, which are quite simplistic compared to actual employees' responsibilities in an actual workplace. Moreover, they focus mostly on the personally controlled devices, which implementation on a big scale in currently dominating open-space offices is questionable. The current study aims to assess the impact of the use of ceiling fans under shared control and increased temperature set-points, on thermal comfort and self-reported productivity, with workers performing their actual work, in a real office space located in Singapore.

2. Methods

2.1. Facilities and measuring equipment

A case study was conducted for six weeks at the Robert Bosch (SEA) Pte Ltd building. To our best knowledge, it was an only commercial company (not related to fan industry) in Singapore that decided to install ceiling fans in its office space and agreed to perform prolonged questionnaire study. Participants worked in two open-space office rooms (WxLxH: 8.0 m × 8.0 m x 4.2 m) and in a private room separate from the main open-spaces (3 m × 4 m) shown in Fig. 1. The space under examination is localized on the first floor and has a glass façade with a south-west orientation.

Within the space, a mechanical ventilation system delivers required air-conditioned outdoor air to the occupants. Separate fan coil units (2 units of Carrier 40LM070 with a total cooling capacity of 12.8 kW per room) control the room's temperature set-points. DC motor ceiling fans (Haiku I-Series 60 in., BigAss Solutions, US) provide elevated air movement within the space. Fans are installed in an array of 3 m × 4 m at the height of 3.5 m from the floor. The maximum power consumption of the installed fans reaches 30 W per fan; however, the fan power consumption related to the speed set points usually used by occupants is no greater than 5 W.

Dry-bulb air temperature, operative temperature and relative humidity were measured at workstations in 5-min intervals using a data logger (HOBO U12-012, Onset, US) with an accuracy of ± 0.35 °C, ± 0.25 °C and ± 2% *RH* respectively (measuring range: −20–70 °C and 5–95% *RH*). We used grey sphere sensors to directly measure the operative temperature [23]. The temperature sensors were calibrated before measurement.

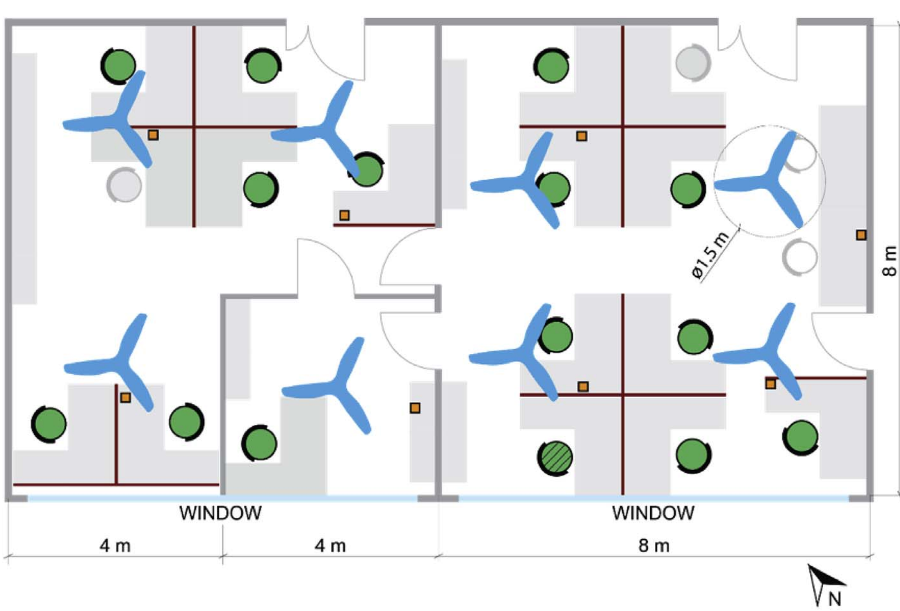

Fig. 1. Plan view of the studied office space. Green seats represent occupants participating in the study (occupant marked with dashed lines submitted invalid generic questionnaire), grey seats occupants who refused to participate and white empty seats. Ceiling fans (1.5 m (60 in.) in diameter) are marked in blue. Orange squares show positions of sensors monitoring dry-bulb and operative temperatures, and relative humidity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

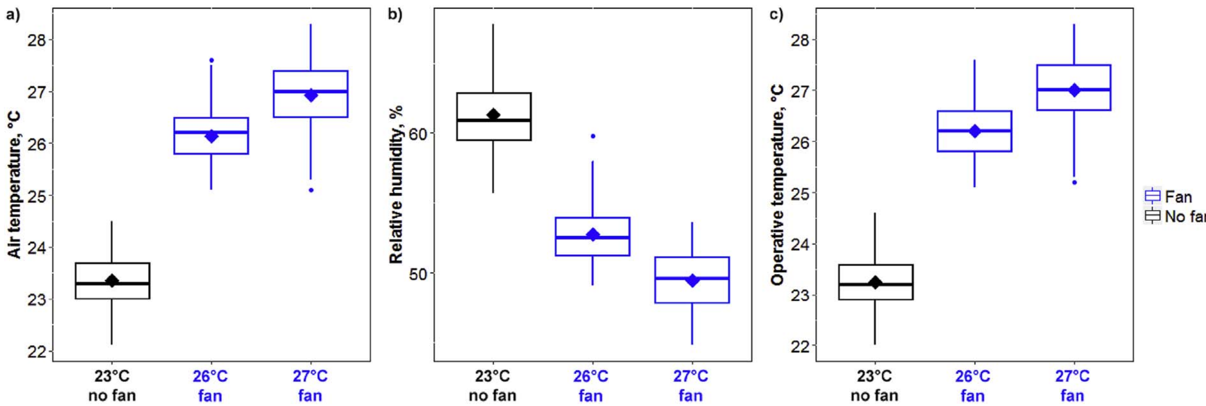

Fig. 2. Statistical distribution of measured indoor environmental parameters during working hours (7:00–19:00): (a) air temperature, (b) relative humidity and (c) operative temperature.

2.2. Study conditions

The study included an examination of three conditions: a typical Singaporean room temperature for commercial buildings of 23 °C [1,24], and two instances of elevated room temperature—26 and 27 °C. The elevated temperature conditions were achieved in two ways: (1) by increasing the air-conditioning set-point to 26 °C, and (2) by turning off the room fan coil units. Set point of 26 °C has been selected as a typical set-point used in the thermal comfort studies for summer conditions [7,11,12,25,26]. The second method of achieving elevated temperature was affected by the heat sources in the space, and operative temperature increased up to 28.5 °C. The aim for this condition was to achieve the highest possible room temperature without installation of additional heaters, which would disturb employees and be unrealistic. The relative humidity was not controlled in the space, but only monitored during the experimental period. Fig. 2 shows statistical data distributions of air temperature, relative humidity and operative temperature in the studied space during working hours. The changes of the hourly averaged operative temperature during the day are presented in Fig. 3. Reported values are averaged measurements at the workstations.

Within the shared environment, air movement provided by ceiling fans was under the control of groups of occupants (on average two people per fan) and individual control in the private room. Occupants manually adjusted the fan set-points with remote controls, which were kept in an easily-accessible and well-known place in the workspace. Table 1 summarizes the three study conditions.

We conducted presented study during six consecutive weeks of dry season—from May 2016 to July 2016. While planning the experiment, we elicited help from department's manager to select an experimental

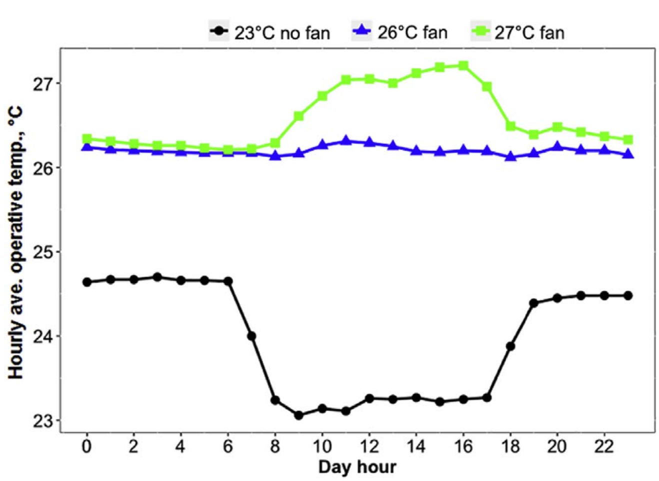

Fig. 3. Daily profile of average operative temperature in the study space.

period, that was the least affected by scheduled events and employees' leave days. Each condition was planned for two sequential weeks (10 working days). In practice, the 27 °C condition was disturbed by the internal 1-day event, which was excluded from the study. Additionally, participants asked to terminate the condition without air-conditioning at the end of second week. To address their concerns, the temperature set-point was set to 26 °C for the last two days of the experiment. Fig. 4 shows the weather data distribution in experimental period for each condition.

2.3. Questionnaire

A psychometrician and two building scientists constructed the survey covering 8 questions in total. The goal of the survey was to characterize whole-body thermal comfort (thermal sensation, thermal acceptability and preferences), air movement (air movement acceptability and preferences), and self-reported worker well-being (i.e., concentration ability, level of sleepiness, and perceived productivity). A demo version of the survey is available online at http://bit.ly/SBBsurvey [27]. Additionally, we included a print screen of the survey in the Appendix.

A continuous scale with 7-points (the ASHRAE scale: −3 - cold; 0 - neutral; +3 - hot) was used for the question examining current thermal sensation [20]. The thermal acceptability, air movement acceptability and self-reported productivity questions were constructed with a 5-point discrete scale to achieve fine gradation in respondents' perception and to make their assessments easier [28]. Occupants' responses were collected five times per day for the whole six-week measurement period. Participants received automated notifications at their workstation computers at fixed hours (every two hours from 9:30 to 17:30). If they were not present at the workstation, their responses were not recorded. To maintain as much ecological validity as possible, we did not want to restrict occupants from their usual habits. We did not give occupants any restrictions regarding their presence at the workstation, type of the activity, clothing, etc. They arrived at the office between 7:00 and 9:00 a.m., performed their regular tasks, partially worked in the laboratory, etc. When present at their workstation, they typically worked on computers in sitting or standing position (estimated metabolic rate of 1.1–1.2 met). Clothing was not monitored during the experiment. In Singapore, the dressing code in office environment is quite rigid and participants dress in business casual style (no tie, short sleeve shirt or T-shirt, long trousers, full shoes—estimated clothing insulation of 0.57 clo).

2.4. Participants

Fifteen employees volunteered to take part in the study (88% of people occupying the study space). One participant submitted an

Table 1
Experimental conditions.

Condition	Time, days	Design conditions		Measured conditions (mean)			Collected sample size	Resampled sample size[c]
		Temperature set point, °C	Group controlled fans	Operative temperature, °C	Relative humidity, %	Fan speed level (max. 6)		
23 °C no fan	10	24	No	23.1	61.5	0	293	480
26 °C fan	12	26	Yes	26.2	53.4	1[a]	355	480
27 °C fan	7	AC off[b]	Yes	26.9	50.3	2[a]	196	480

[a] Estimated power consumption of the fan: 2 W at set-point 1; 5 W at set-point 2.
[b] Air conditioning fan coil within the study zone was turned off. The mechanical ventilation kept on working.
[c] More details in section 2.5.

invalid generic questionnaire. Demographic information about fourteen participants is summarized in Table 2. All participants were acclimated to the tropical climate in which the study took place [29]. 11 employees had lived in the location's tropical climate for more than 18 months at the time of the study. The remaining three participants had lived in the tropics for 3–7 months, which is sufficient time for short-term acclimatization [29].

We asked participants what type of cooling appliances they use in their living environment and their preferred way to cool down when warm in the background portion of our survey. As shown in Table 3, participants actively use both air conditioning and fans.

2.5. Statistical analyses

Analyses were carried out using R version 3.3.2 software [30]. Because participants followed their regular work schedules (partially worked in laboratories instead of the regular workstation, attended delegacies, took annual leaves, etc.), the obtained data was imbalanced with regards to the conditions and response numbers from each participant. The imbalanced dataset has been processed using a synthetic minority over-sampling technique (SMOTE) available in the "Data Mining with R (DMwR)" package [31–33]. This technique uses bootstrapping and k-nearest neighbor to synthetically create additional observations of the event. This allowed us to balance number of responses between participants and cases.

Shapiro-Wilk's W test yielded a non-normal distribution of the data and residuals ($W = 0.44$-0.90, $p < .001$) for all survey variables (except for those collected in the background/demographic section of the survey). Use of the Brown-Forsythe test [34] yielded homogeneity of variance for sleepiness levels and self-reported productivity. All other measured variables showed non-equality of group variances ($p < .001$). Therefore, we used Friedman's analysis of variance (ANOVA) and Wilcoxon signed-rank tests for further analysis [35]. Spearman's rank coefficient was used to measure the degree of similarity between variables, and to assess the significance of the relationship between them.

The data distributions are shown with box-and-whisker plots (the thick horizontal line is the median, the rhombus represents the mean, and the circles are outliers). Graphs were prepared using "GGplot2" [36]. We report the numerical summary data as medians with the interquartile range (25th and 75th percentiles) in parentheses (e.g., *Mdn* = 4, IQR [4,5]).

3. Results

3.1. Thermal responses

A nonparametric local polynomial regression [37] was used to relate reported whole-body thermal sensation and operative temperature (Fig. 5; Spearman's rank correlation: $r_s = 0.70, p < .001$). Results show that an air-conditioning cooling set-point of 23 °C (typically used in Singapore) results in a reported slightly-cool thermal sensation (*Mdn* = −1.1, IQR [−2.0, −0.1]). The increase of the set-point temperature to 26 °C along with use of the elevated air movement resulted in a significant increase in a reported thermal sensation closer to "neutral" (*Mdn* = 0.0, IQR [0.0, +0.4]), Wilcoxon signed-rank: $Z = -16.9$, $p < .001$, $r = 0.44$, which was maintained up to 26.8 °C. Further increase of the room temperature resulted in a significant increase to a reported "slightly warm" thermal sensation (*Mdn* = +0.7, IQR [+0.1, +1.2]), Wilcoxon signed-rank: $Z = -10.9$, $p < .001$, $r = 0.29$.

Fig. 6A presents responses of thermal acceptability in a dichotomous way (acceptable vs. unacceptable). Acceptability was determined by clustering "neutral" through "very acceptable" responses (see acceptability scale). When the temperature set-point was 26 °C and fans were in use, the highest level of thermal satisfaction was reported (91% of all respondents indicated acceptability). This was the only condition that fulfilled requirements of widely accepted indoor environmental standards (ASHRAE 55 [20]; EN 15251 [19]). Although lower than in the

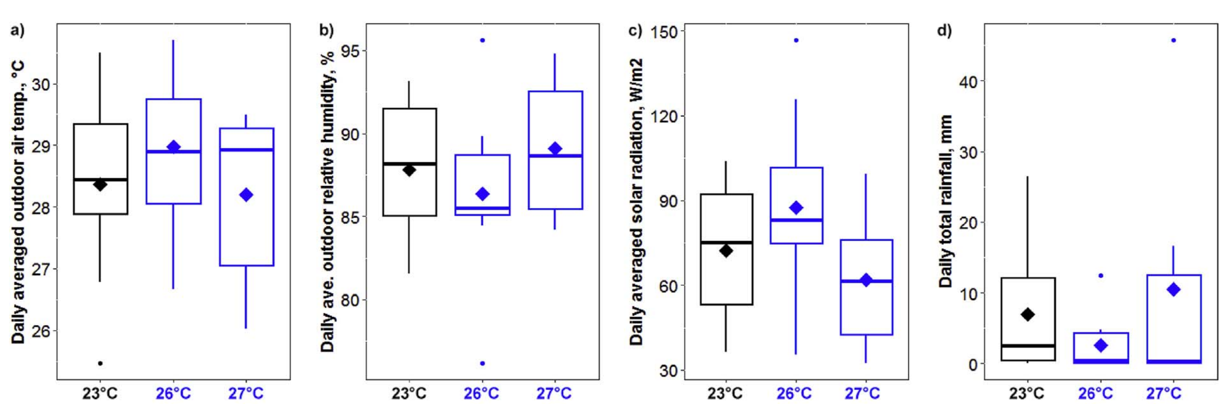

Fig. 4. Statistical distribution of daily averaged outdoor environmental conditions: (a) air temperature, (b) relative humidity, (c) solar radiation and (d) total rainfall. Experimental dates for 23 °C no fan: 6–19 Jun 2016; 26 °C fan: 23 May–5 Jun and 30 Jun–1 Jul 2016; 27 °C fan: 20–29 Jun 2016.

Table 2
Participant demographics (mean ± standard deviation for normally distributed; median (1st quartile, 3rd quartile) for non-normally distributed).

Gender	Age (yrs.)	Height (cm)	Weight (kg)	BMI[a] (kg/m^2)	In tropics (yrs.)
All	32.5 (30.2, 36.0)	172.9 ± 8.7	69.4 ± 10.2	23.1 ± 2.0	3.3 (1.5, 5.7)
Males (11)	32.0 (30.5, 38.0)	175.3 ± 8.1	72.7 ± 8.6	23.6 ± 1.7	1.7 (1.0, 7.0)
Females (3)	32.7 ± 3.5	164.0 ± 3.6	57.3 ± 5.5	21.3 ± 2.4	5.4 ± 0.4

[a] Body Mass Index, BMI = Weight/Height^2; BMI between 18.5 and 25 kg/m^2 indicates normal (healthy) weight according to WHO.

Table 3
Participants' cooling habits.

Appliance	Appliances used in:			Preferred way of cooling
	Bedroom	Living room	Office	
Air conditioner	13 (93%)	7 (50%)	14 (100%)	7 (50%)
Fan	8 (57%)	9 (64%)	10 (71%)	7 (50%)
Open window	3 (21%)	9 (64%)	–	–

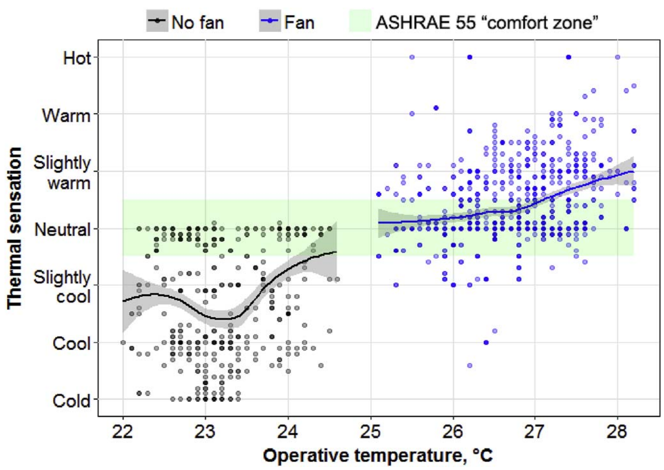

Fig. 5. Assessment of whole-body thermal sensation correlated with an operative temperature at workstations (LOESS regression with 95% confidence intervals). The green shaded area represents ASHRAE 55 [20] acceptable range. Darker marks represent higher number of data points. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

previously described condition, participants also reported acceptability in the other two conditions as well (58% and 77% at 23 °C and 27 °C respectively). Thermal acceptability in the condition with a temperature of 26 °C with fans was significantly higher than in both the 23 °C without fans condition (Wilcoxon signed-rank: $Z = -11.1$, $p < .001$, $r = 0.29$) and the 27 °C with fans condition (Wilcoxon signed-rank: $Z = 3.49$, $p < .001$, $r = 0.092$). Moreover, the acceptability was also significantly higher when air-conditioning was turned off with fans in operation than at the set-point of 23 °C (Wilcoxon signed-rank: $Z = -8.96$, $p < .001$, $r = 0.24$).

Participants' thermal preference responses are shown in Fig. 6B. The results indicate that occupants preferred the thermal environment in which the temperature was 26 °C and fans were in use over others: specifically, 78% of responses indicated a desire for "no change" in thermal sensation. Conversely, 63% of all responses in the 23 °C condition indicated a preference for a warmer environment at their workstation. Turning off the air conditioning, in contrast, resulted in 54% of all responses desiring a cooler thermal environment—even when ceiling fans were in operation.

3.2. Air movement and fan speed levels

In general, the air movement acceptability was high in all conditions (Fig. 6C). The satisfaction in air movement increased when fans were in operation: 97% satisfaction at 26 °C and 93% at 27 °C. However, the analysis on the discrete scale showed that these differences were not significant, Friedman ANOVA: $\chi^2(2) = 0.41$, *n.s.*

Fig. 6D presents the percentage of responses of air movement preference. A desire for "no change" was dominant in all conditions, with a maximum value of 88% at a temperature set-point of 26 °C with ceiling fans in operation. The increase of the room temperature resulted in an increased demand for air movement: 9% in the 26 °C condition and 21% in the 27 °C condition.

The installed ceiling fans have seven speed set-points (level 0 - turned off, minimum: level 1–35 rpm, maximum: level 6–200 rpm; BigAss Solutions, US). The selected fan speed levels and operative temperature were moderately correlated (Spearman's rank correlation: $r_s = 0.66$, $p < .001$). Fig. 7A shows how fan usage changed as a function of the operative temperature together with its correlation to air speed at workstation directly below the fan. Level 1 (air speed of 0.2 m/s) was the most preferred fan speed set-point at operative temperatures up to 26.4 °C, and level 2 (~0.6 m/s) was most desired at higher temperature values. High air movement acceptability was maintained up to fan speed level 3 (~0.8 m/s), and dropped to "neutral" at speed level 4 (Fig. 7B). Occupants did not exceed usage past speed level 4 (~1.0 m/s), even though the operative temperature in the space rose above 28 °C.

3.3. Self-reported productivity

Participants reported consistently high productivity in all conditions. Spearman's rank correlation showed a significant correlation between self-reported levels of sleepiness, ability to concentrate, and work productivity (r_s = 0.79-0.90, $p < .001$). Descriptive statistics, presented in Fig. 8, show that an increase in room temperature and corresponding air movement did not affect the analyzed parameters. Statistically significant differences are negligible for the practical use of the results (small effect size, r = 0.022-0.075).

Responses to the three analyzed occupant performance variables were moderately correlated with thermal sensation acceptability (Spearman's rank correlation: r_s = 0.51-0.65, $p < .001$) and air movement acceptability (Spearman's rank correlation: r_s = 0.52-0.61, $p < .001$). Fig. 9 presents the relationship between these variables and how an increase in thermal satisfaction positively affects self-reported productivity variables. Nonetheless, high levels of monitored self-reported parameters were also observed when occupants were thermally uncomfortable. The nonparametric local polynomial regression shows that the highest levels of concentration and work productivity tended to be achieved at "neutral" thermal sensation (from +0.2 to +0.4). Alertness level is the only parameter with non-monotonic trend and highest values were reported at both "cold" (−3.0) and "neutral" thermal sensation (from +0.2 to +0.4).

3.4. Energy usage

The electrical energy used by fans in the fan coil units was measured for half of the studied space (1 room). Table 4 presents recorded daily data together with electrical usage of ceiling fans in the corresponding zone. Unfortunately, a communication error with the server resulted in

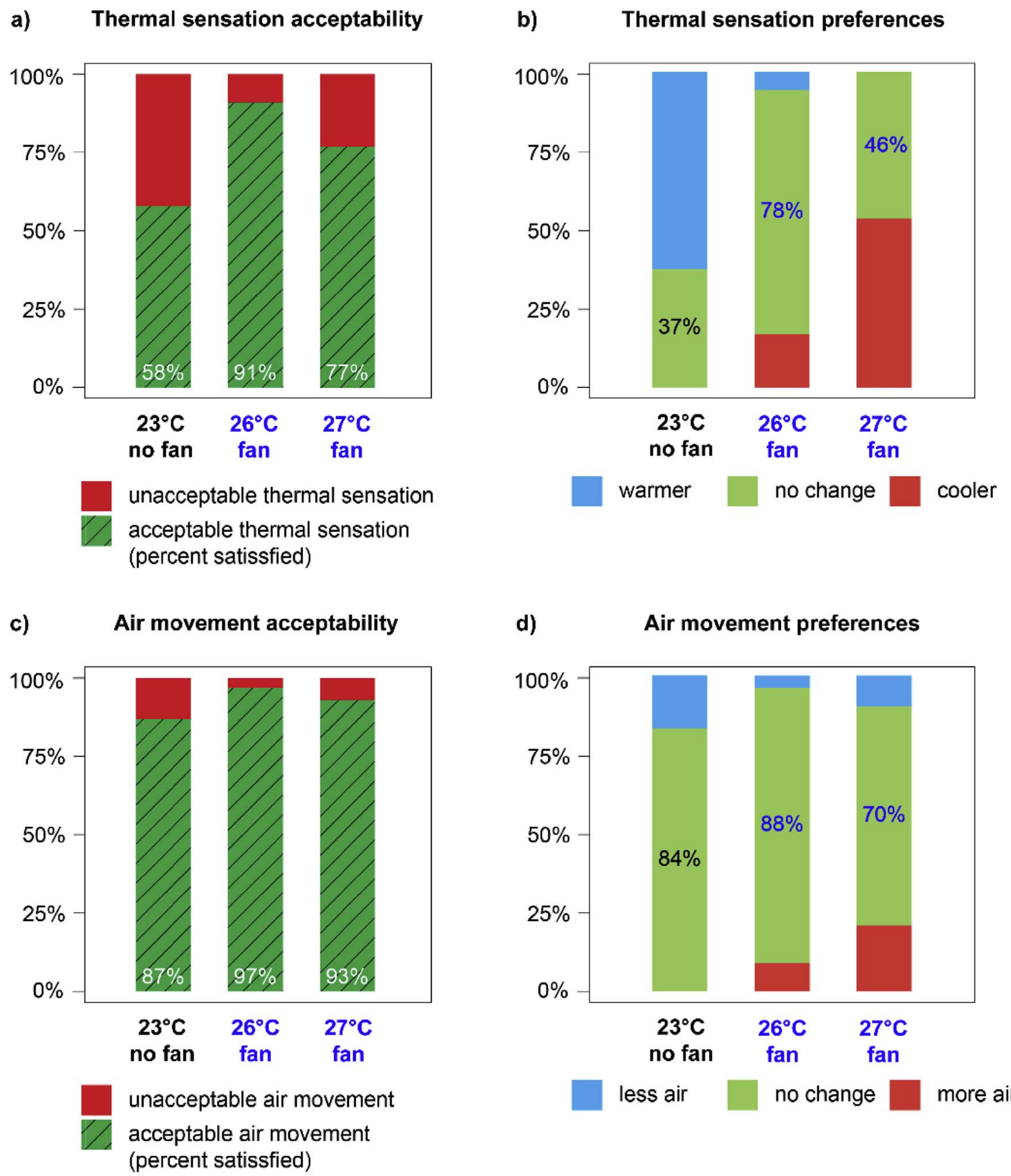

Fig. 6. Acceptability and preferences for thermal environment regarding thermal sensation (a, b) and air movement (c, d). The sample size was 480 responses for each condition.

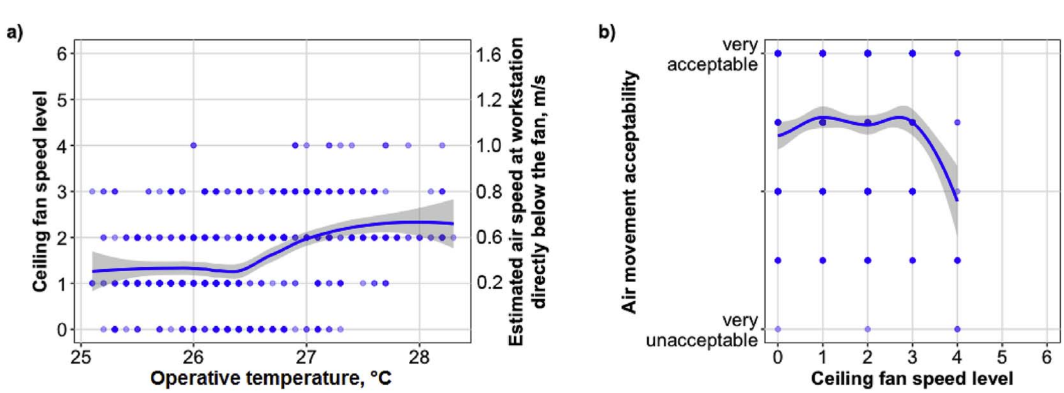

Fig. 7. Selected fan speed level correlated with (a) operative temperature at the workstation and (b) air movement acceptability (LOESS regression with 95% confidence intervals). Darker marks represent higher number of data points.

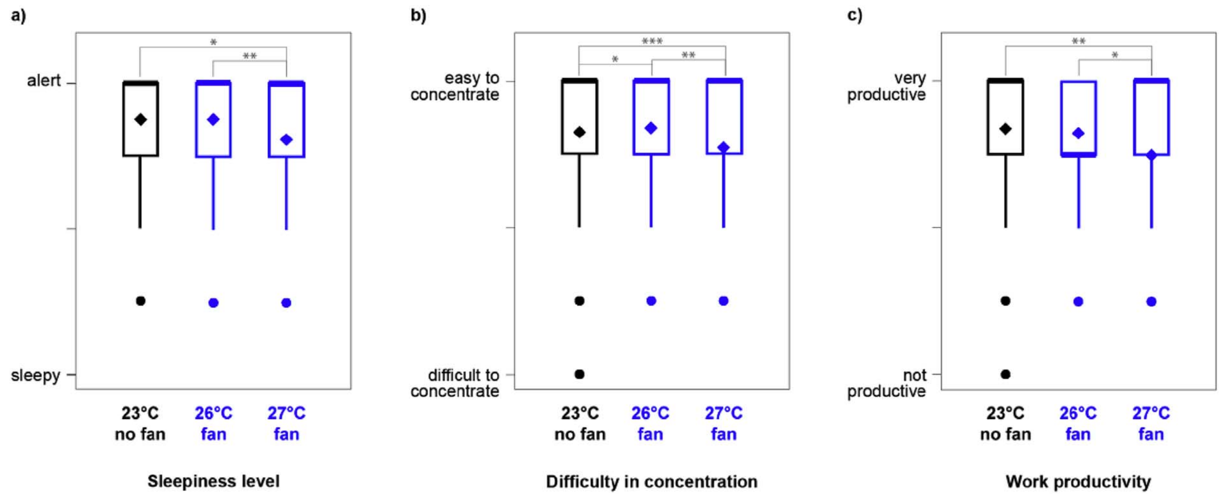

Fig. 8. Assessment of self-reported levels of sleepiness (a), concentration (b), and productivity (c). Asterisk shows the significance at: * $p < .05$, ** $p < .01$, *** $p < .001$. For all the cases the effect size is negligible, so there are no practical differences.

recording data only for nine days from a 22-day measurement period when the air-conditioning was in operation (23 °C condition without fans and 26 °C with operating fans, Table 1).

We calculated the daily average values for each study condition using the number of hours in which the space was occupied each day as weight factors. The time-averaged daily total consumption for the 23 °C condition was 34.45 kWh. Taking into account that climate in Singapore is relatively stable and there were 260 working days in 2016, estimated annual energy use intensity for analyzed space (area of 64 m^2) at the 23 °C condition is 140 kWh/m^2yr. The increase of the temperature set-point to 26 °C resulted in a total estimated annual energy savings of 44 kWh/m^2yr for fan coil fans. At the same time, the energy used for ceiling fans represented no more than 1% of the total energy consumption. Turning off the air-conditioning system, and fully depending on the ventilation system combined with ceiling fans, did not substantially increase the energy use of the ceiling fans. The time-average daily energy usage for this experimental condition was 0.16 kWh (annual consumption of 1 kWh/m^2yr).

4. Discussion

Existing laboratory studies examining occupants' experiences with personally controlled standing/desk fans [7,9,12] and ceiling fans [8,11] show that thermal comfort can be achieved up to 30 °C and 60% *RH* without discomfort from elevated temperature, humidity, air movement, or eye dryness regardless of fan type. However, based on present work conducted in a real-world office environment, we recommend operative temperature not to exceed ∼27 °C when ceiling fans are under shared control of occupants (Fig. 5). For instance, when the air-conditioning fan coils were turned off, and the room temperature increased above 28 °C at which point participants complained about the unpleasant thermal environment which distracted them from their usual work tasks. Conversely, when the room temperature was lower, thermal sensation and acceptability replicated findings of Schiavon et al. [7]. In both studies, more occupants found the thermal environment more acceptable at 26 °C with air movement from fans, than they did in environments with a set-point of 23 °C. Also, participants reported the highest percentage of a desire for “no change” in the condition in which the temperature was 26 °C with fans, thus suggesting that thermal distraction was lowest in this condition.

A field study examining the use of ceiling fans in Brazil showed that an air speed of at least 0.4 m/s and 0.5 m/s was required to achieve 80% satisfaction from occupants as it related to air movement at an operative temperature of 26 °C and 28 °C respectively [13,38]. In that case, the majority of participants preferred more air movement and reported preference for air speed values close to or higher than the 0.8 m/s. This finding is similar to other lab studies that reported preferred air speeds of 0.6–0.7 m/s at 26 °C and 1.0–1.2 m/s at 28 °C under personal control [7–9,11,12], which suggests a tolerance for higher air speeds than suggested by ASHRAE 55 [20]. However, the present study's results differed from previous findings [8,13,38]; specifically, occupants without personal control, similarly reported high acceptability of air movement with air speed up to 0.6 m/s, but did not tolerate air speed above 1.0 m/s. The present outcome is more consistent with Toftum's [10] conclusions, which suggest that though it is possible to maintain thermal comfort and sensation with high air velocity at elevated temperatures, the majority of people prefer lower air velocity and a temperature in the comfort range of 23–25 °C. It is thought that the pressure of high air velocities on the skin, and the general disturbance created by the air movement, may cause discomfort for occupants.

One major difference between these studies that may be worth comparing, is the degree of control an occupant has. In the present study, occupant had shared control—whereas in the other mentioned studies [7–9,11,12], occupants had direct personal control. Perhaps tolerance is influenced by the degree of control one has. Another important aspect to consider is the way in which an occupant is interacting within the space he or she occupies, and how that may influence their tolerance towards the environmental conditions. For instance, the Brazilian study mentioned above was conducted in drawing and model building classes in architecture studios and classrooms. These environments were selected on purpose, because it was thought that the high air speeds would not disturb the students as they carried out their daily activities. Another point to consider is the participants themselves. Most of the mentioned laboratory studies were conducted within undergraduate student populations, and thus may not be representative of a typical office worker or work environment [8,11,12]. Moreover, laboratory tests have most often been designed to take 45–90 min per condition. The current study, in contrast, was done over a prolonged period, with full-time working professionals, focused on their regular tasks that required engagement in critical thinking (e.g., development and evaluation of new technologies and system concepts, preparation and supervision of experiments for validation, *etc.*). By examining real employees conducting actual work (versus students completing simulated work), this study was able to ensure higher engagement than laboratory test participants, in a more ecologically valid environment.

Self-reported work performance remained stable across the tolerable temperature ranges of all three conditions. These results are similar

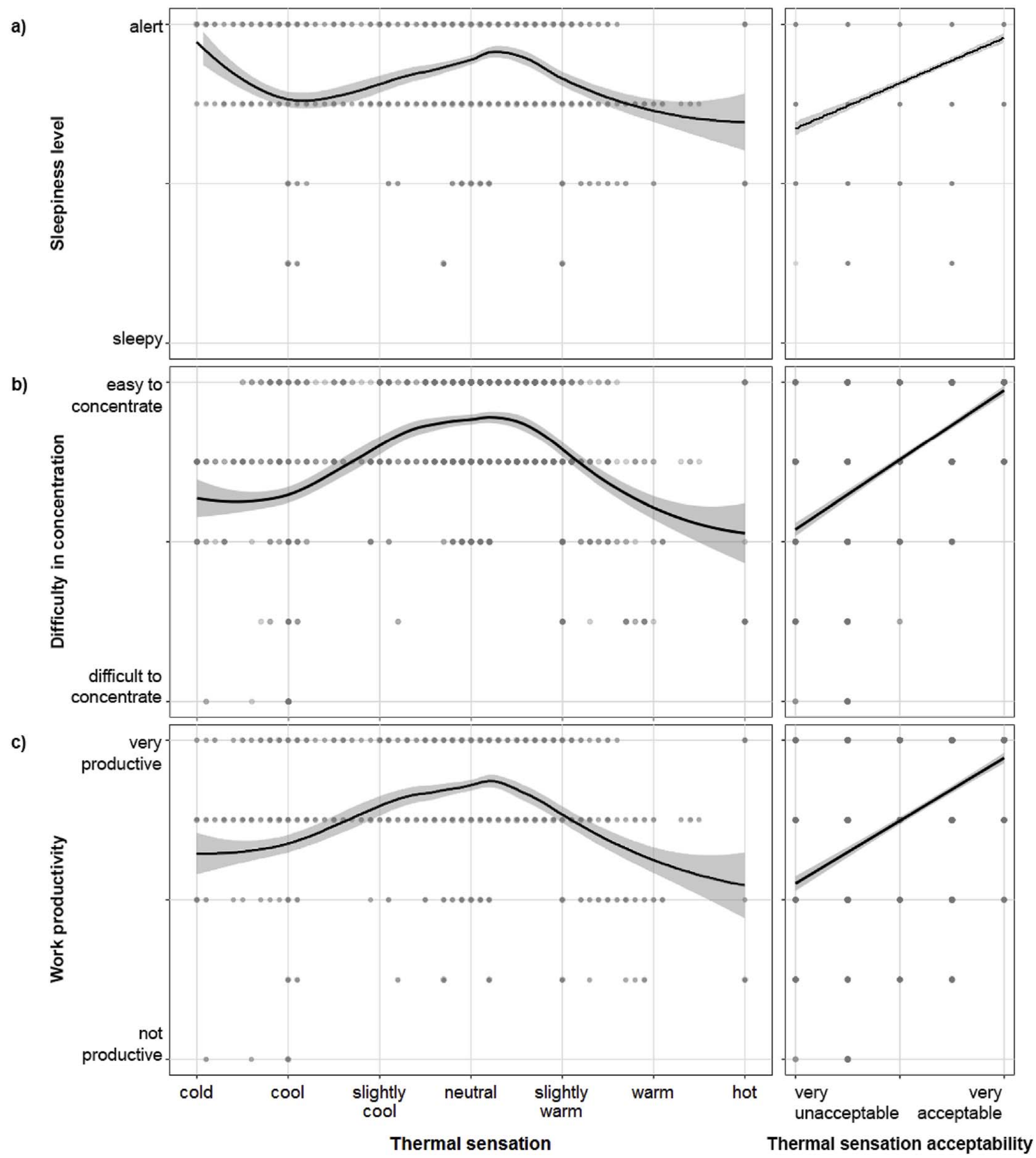

Fig. 9. The effect of thermal sensation and its' acceptability on (a) sleepiness, (b) concentration, and (c) productivity; (LOESS and GLM regression with 95% confidence intervals; n = 1440 responses). Darker marks represent higher number of data points.

to those presented by Schiavon et al. [7] when elevated air movement was in use. The present findings suggest that room temperature cannot be used as a single parameter for determination of optimal thermal conditions when trying to promote the highest work performance potential in occupants. However, if self-reported work performance response are plotted as a function of thermal sensation, an inverted-extended-U relationship emerges. A similar relationship has been reported in other related studies; though there are some variations [39–42]. In one example, optimal performance was achieved with the presence of a reported slightly cool thermal sensation (from −1 to −0.21) [40]. Conversely, in our recent work, the optimal thermal sensation reported is shifted more towards a sense of a neutral sensation (from +0.2 to +0.4). When examining all of this work together, one could conclude that people have the ability to adapt quickly and preform effectively, as long as the environmental conditions are kept within the range of comfort acceptability [43]. It should be noted that the present data reflects that self-reported performance was highest when both occupant acceptability of thermal sensation and air movement was highest (as suggested by Tanabe et al. [44]).

In the current work, an increase in the temperature set-point from 23 °C to 26 °C, not only resulted in an increase in occupant satisfaction, but also in substantial savings of electrical energy used by fans is fan coils for comfort cooling. Energy savings of 44 kWh/m^{2}yr were achieved only by adjusting the temperature set-point at the air-conditioning fan coil units (Table 4). This finding supports previous work focused on hot and humid climates [3,5,45].

Energy used for the preparation of outdoor air is not included in the present calculations. However, the outdoor ventilation rate and operating conditions were maintained constant (i.e., supply air temperature set-point, airflow rate, and chilled water temperature). The high cooling capacity of air-conditioning fan coils, and low heat loads in the zone, resulted in a fast space cooling (~0.5–0.8 °C room temperature drop in 30 min) without substantial change in the moisture content of the space. The specific humidity remained at the same level in all studied conditions (11.0–11.3 g/kg). Therefore, the decrease of relative humidity (Table 1) is a result of an increase in the room temperature set-point; which is consistent with previous findings [3]. The current results also illustrate that when outdoor ventilation remains

Table 4
Daily consumption of electrical energy measured in one zone during the experiment. The maximum total energy values for each condition are in bold font.

Case	Date	Mean outdoor air temp., °C	Total number of working hours	Fan coil energy usage, kWh	Ceiling fan energy usage, kWh	Total energy usage, kWh	Time-averaged total daily energy usage, kWh
23 °C no fan	6/16/2016	27.8	6.0	24.03	–	24.03	34.45
	6/17/2016	25.5	8.0	42.27	–	**42.27**	
26 °C fan	5/26/2016	28.9	7.0	20.59	0.16	20.75	23.56
	5/27/2016	30.7	9.5	19.29	0.12	19.41	
	5/30/2016	27.9	10.5	27.87	0.17	**28.04**	
	5/31/2016	29.8	9.5	23.01	0.16	23.18	
	6/01/2016	26.7	12.0	18.64	0.07	18.72	
	6/02/2016	28.1	7.0	12.85	0.14	13.00	
	6/30/2016	30.5	7.0	22.71	0.12	22.83	
27 °C fan	6/20/2016	28.7	9.0	–	0.20	0.20	0.16
	6/21/2016	29.7	9.0	–	0.22	**0.22**	
	6/22/2016[a]	26.5	3.5	–	0.09[a]	0.09[a]	
	6/24/2016	26.0	9.0	–	0.13	0.13	
	6/27/2016	29.3	9.0	–	0.14	0.14	
	6/28/2016	28.9	9.0	–	0.17	0.17	
	6/29/2016	28.2	9.0	–	0.11	0.11	

[a] Half day in the office.

unchanged, an increase in a room's temperature does not lead to moisture problems as previously thought [1,2,46].

Previous laboratory studies, energy simulations, and the current fieldwork confirm the benefits of using elevated temperature set-points in tandem with air movement in the tropics. Based on the findings, we recommend changing the current limits set forth in the thermal environment parameters stated in Singaporean standard SS 553 (2016). The air speed limit of 0.3 m/s should be removed, and the operative temperature range increased to a range of 25–27 °C. Easing the restrictions of the current requirements would allow opportunity for both improving occupants' experience and satisfaction, and result in significant air-conditioning energy savings.

4.1. Limitations

Elevated air movement provided by ceiling fans and a room temperature set-point of 26 °C have been consistently and regularly used in studied office before start of the experiment. It should be noted, that the norm in the examined environmental conditions could have had an impact on the results obtained at the set-point of 23 °C. More specifically, this may adapt participants to the temperature of 26 °C and decrease their acceptability for 23 °C [47]. However, the same high level of thermal satisfaction at condition of 26 °C with fans was previously obtained in controlled laboratory conditions [7], which suggests that the thermal satisfaction for this conditions has not been falsely increased.

We were not able to include a control group in the current work because we were unable to expose occupants to a controlled condition in which ceiling fans were in operation. Additionally, the number of the subjects (n = 15, with one participant who submitted invalid demographic questionnaire) limits the ability to generalize our findings to the broader population, or to explore individual differences such as sex, age, culture, and ethnicity. Future work would benefit from increasing the diversity and sample size of the population studied. Further, replication of these results should be explored in other tropical climates with differing cultural environments.

The energy assessment presented in the paper is based on a simplified metering of the electrical energy usage of fans in air-conditioning fan coils and ceiling fans in one tested room. We did not have the ability to monitor the operating parameters of the fan coil and ventilation system in detail. Moreover, the unexpected problems with our data server resulted in a shortened measurement period. We include these results in this paper for illustrative purposes only; however, it is important to note they are congruent with Duarte and colleagues' [3] detailed energy simulations performed for the Singaporean benchmarked office.

5. Conclusions

We verified in a real-world office environment in the tropics that if we increase the temperature setpoint from 23 °C to 26 °C, while simultaneously providing occupants shared control over ceiling fans, we can obtain a major increase in thermal comfort (i.e., thermal acceptability increasing 59%–92%) while maintaining high alertness, ability to concentrate, and self-reported productivity. At the same time, the energy usage for comfort cooling can be decreased by roughly a third, and the relative humidity reduced. In rooms with shared control over ceiling fans, the temperature setpoint should not be higher than 27 °C.

Singaporean standard SS 553 (2016) should be adjusted to reflect the current findings; an air speed limit of 0.3 m/s should be removed and the operative temperature range should be increased to 25–27 °C.

These research findings show that self-reported productivity (alertness, level of concentration, and work productivity) improves when individual thermal satisfaction increases. The findings reflect that the environmental conditions examined here provide a clear benefit for improving workplace conditions.

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Appendix. Questionnaire

The “right now” survey was constructed by a psychometrician and two building scientists. It aims to characterize whole-body thermal comfort, air movement, and self-reported work well-being (concentration, level of sleepiness and productivity). Occupants' response was collected through survey shown in Fig. A1 five times per day for the whole six-week measurement period.

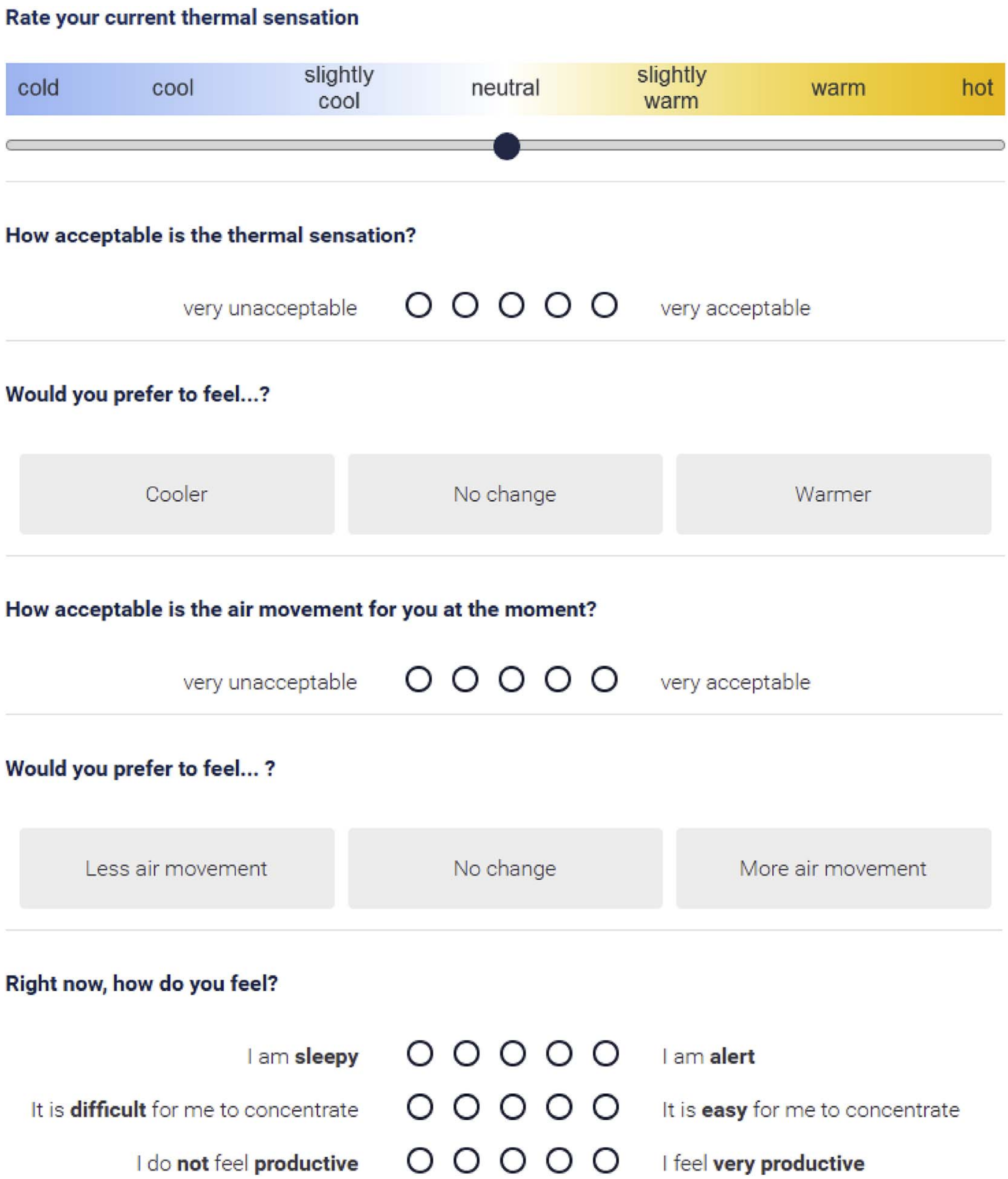

Fig. A1. "Right now" survey used in the field studies.

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