Comfort under personally controlled air movement in warm and humid environments

Yongchao Zhai [a, b], Hui Zhang [b], Yufeng Zhang [a*], Wilmer Pasut [b], Edward Arens [b]
Qinglin Meng [a]
[a] State Key Laboratory of Subtropical Building Science, Department of Architecture, South China University of Technology, Wushan, Guangzhou, 510640, PR China
[b] Center for the Built Environment, University of California, Berkeley, CA 94720

Abstract

This study examined the effects of personally controlled air movement on human thermal comfort and perceived air quality (PAQ) in warm-humid environments. At temperatures 26, 28, and 30°C, and relative humidity (RH) 60% and 80%, sixteen human subjects were exposed to personally controlled air movement provided by floor fans in an environmental chamber. The subjects reported their thermal sensation, thermal comfort, and PAQ during the tests. Two breaks periods with elevated metabolic levels were used to simulate normal office activities. Results show that with personally controlled air movement, thermal comfort could be maintained up to 30°C and 60% RH, and acceptable PAQ could be maintained up to 30°C 80% RH, without discomfort from humidity, air movement or eye-dryness. Thermal comfort and PAQ were resumed within 5 minutes after the breaks. The 80% acceptable limit implicit in comfort standards could be extended to 30°C and 60% RH. The average energy consumed by the fans for maintaining comfort was lower than 10W per person, making air movement a very energy-efficient way to deliver comfort in warm-humid environments.

Keywords: Thermal comfort; Perceived air quality; Warm-humid; Air movement; Personal control; Low energy.

1. Introduction

Compressor cooling in buildings is already the main contributor to peak load in long tropical or sub-tropical summers, affecting both energy use and electrical grid safety, and this trend is going to accelerate in the coming decades with the cooling demand growth in South China, South-east and South Asia. In the face of the huge energy impacts that this increase is causing, one must examine alternative ways of achieving comfort in warm-humid environments.

In warm environments, air movement has the potential to conserve energy while maintaining occupants' comfort. Field studies in warm-humid climates have shown that occupants remained comfortable in naturally ventilated buildings with natural wind and fans [1-7]. In air-conditioned buildings, a reanalysis of ASHRAE field study database also shows that a majority of occupants preferred more air movement when their thermal sensations are slightly warm or warmer [8].

Recently, ASHRAE Standard 55 "Thermal environmental conditions for human occupancy" increased allowable air movement for comfort in warm environments [9], providing more opportunities for air movement design for cooling [10]. Air movement has long been shown to be effective at increasing convective and evaporative heat loss in warm environments [11-14]. Laboratory studies have found that thermal comfort can be well maintained by personally controlled horizontal air movement in ambient temperatures as high as 27.8°C and 30°C [15][16]. Recent studies have shown that a 3W personal fan maintains a neutral thermal sensation up to 30°C and 50% RH [17].

Of such studies, relatively few have combined high temperatures and high humidity. One of these, by Tanabe and Kimura [18] tested horizontal air movement provided by an array of box fans on sedentary subjects wearing 0.6clo, and found that comfort could be maintained at 31°C, 50% RH with 1.6 m/s airspeed, and at 29°C, 80% RH with 1.4 m/s air speed. Kubo et al. [19] tested self-selected frontal airflow with subjects wearing 0.35 clo at 30°C and 80% RH. Subjects chose a cooler-than-neutral thermal sensation by selecting an average air speed of 1.27 m/s at 30°C and 80% RH. Even higher air speeds (up to 3 m/s) has been preferred by subjects in Thailand [20] and Hong Kong [21] at temperatures higher than 30°C and at RH values as high as 85%.

Studies have also shown that air movement significantly improves people's PAQ in warm temperature and moderate humidity conditions up to 30°C [17][22-23], and in humid environment up to 28°C [24-26], although the causal mechanism behind this is not well understood.

However, the cited research has mainly focused on overall thermal sensation, paying less attention to general acceptability of thermal environment, PAQ, humidity and air movement, and possible eye discomfort due to high air speeds. Previous studies used large fan-box or personalized ventilation systems; less has been done with regular room fans, which are easier and cheaper to implement in buildings. Another issue is human reaction to thermal transients, because air movement, unlike temperature and humidity, is almost never uniform across space, and the ability of air movement to restore comfort after periods of time spent in still air is important. These issues are of great importance because answers to these questions might impact the wide adoption of air movement devices.

The aims of the study were to: (1) examine the ability of personally controlled low-energy fans to maintain thermal comfort and PAQ in warm-humid environments; (2) examine the ability of air movement to restore thermal comfort and PAQ after a short burst of activity; (3) determine the threshold values for temperature and humidity under which acceptable comfort can be maintained with personally controlled air movement.

2. Methods

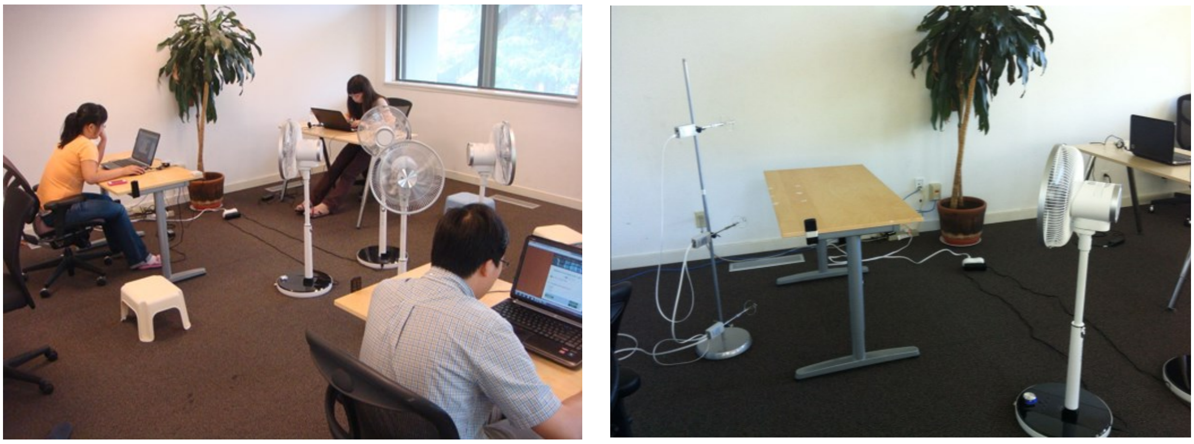
The experiments were carried out at the environmental chamber at the Center for the Built Environment (CBE), University of California, Berkeley in June 2012.

2.1. Facilities

2.1.1 Climate chamber

The CBE climate chamber measures 5.5m×5.5m×2.5m, controlling temperature to an accuracy of ±0.5°C, and RH ±3%. The chamber has windows on two sides, South and West. The windows are well shaded by fixed external shades. The windows temperature is controlled by a dedicated air system. The room air temperature is controlled and ventilated by 8 floor grill diffusers, and the air is exhausted through a ceiling return grill. The outdoor flow rate in this study was around 85-104 L/s. Since the maximum number of occupants was 5 (four subjects and one experimenter), the minimum outdoor air supply rate was between 17.0 and 20.8.L/s person, much higher than the current requirement for office buildings (4.3 L/s.person) [27].

Fig. 1 shows the experimental setup. The chamber was set up to simulate a typical open plan office without partitions. Four workstations (WS) were set up so that four subjects could be tested at the same time. Each workstation was assigned a floor fan, a laptop and a mesh chair. The fans were placed in the middle of the room, blowing air toward the corners in order to minimize interaction between the airflows.



a. Chamber configuration b. Air speed measurement

Fig. 1. Layout of the test chamber and air speed measurement

2.1.2 The fans

The commercially available fan is very energy efficient and consumes only 2 to14 W for fan speed settings 1 to 7 (Table 1). Each fan was placed 1.5m away from the position of the subject. The subjects controlled the fan speeds with a remote controller. Mean air speeds (1.1m height at where the subjects sat) ranged from 0.4 m/s to 1.7 m/s from level 1 to level 7 (Table 1).

Table 1 Fan power and measured air speed at each setting

level	Power (W)	Air speed (m/s)				
		ws 1	ws 2	ws 3	ws 4	mean
0	1*	0.05	0.05	0.05	0.05	0.05
1	2	0.49	0.46	0.45	0.41	0.44
2	3	0.54	0.58	0.56	0.61	0.57
3	4	0.65	0.72	0.66	0.71	0.69
4	7	1.19	1.30	1.25	1.34	1.27
5	9	1.28	1.42	1.44	1.40	1.39
6	11	1.54	1.55	1.62	1.63	1.59
7	14	1.72	1.70	1.73	1.74	1.72

*Plug load

2.1.3 Physical measurements

Room temperature and RH were measured continuously with HOBO Temperature and RH data loggers attached to the back of each table during all the tests. The accuracy of temperature measurement was ± 0.35°C, and RH accuracy was ± 2.5%.

Air speed was measured with omnidirectional hotwire anemometers (Sensor Inc., with a response time of 2s and an accuracy of 0.02 m/s ± 1.5% of reading). Measurements were made before and after the experiment to characterize the air speed at each workstation, at the 0.1m, 0.6m, and 1.1m levels. Air speeds were determined for each of the available fan speeds. During the tests, the fan power was measured each minute with wireless power meters with 1W accuracy, to determine the fan speed levels (Table 1) from which the air speeds at the workstation could be derived.

Indoor CO2 level was measured in the middle of the test chamber, and outdoor CO2 was measured in the supply duct, both with Vaisala CARBOCAP® GMW115Transmitters, at an accuracy of ±2 % of range and ±2 % of reading.

Prior to the experiment, all these test instruments were calibrated against higher accuracy instruments.

2.2. Test conditions

Test conditions (Table 2) were selected to represent the typical temperature and humidity levels in free running buildings in warm-humid climates, based on the ASHRAE RP 884 database [28] and the extensive field data from naturally ventilated buildings in Guangzhou [5]. The corresponding ET^*, SET (at still air and 0.1 m/s), PMV, and enthalpy values are also included in the table.

Table 2 Test conditions

Test conditions	T (°C)	RH (%)	ET^* (°C)	SET (°C)	PMV	Enthalpy(KJ/kg)
1	26	60	26.3	25.7	0.12	58.34
2	26	80	27.0	26.4	0.26	69.37
3	28	60	28.5	28.0	0.67	64.51
4	28	80	29.7	29.4	0.82	77.00
5	30	60	30.7	30.4	1.42	71.15
6	30	80	32.6	32.5	1.59	85.29

2.3. Subjects

Eight male and eight female subjects participated in the tests (see Table 3 for the subjects' anthropology data). The subjects were instructed to dress in typical summer clothes (0.5 clo) – T-shirt or short sleeve shirts, jeans or light pants, underwear, light socks, and sandals. Mesh chairs were used to minimize the additional insulation of the chair. The subjects were allowed to lean forward or backward as in real offices, but not allowed to stand up or move around during the tests.

Prior to tests all the subjects attended a training session to get familiar with the chamber, test procedure, control of fans, and survey questions.

Table 3 Subjects' anthropology data

Sex	Sample size	Age	Height (m)	Weight (Kg)	BMI[#]
Female	8	30.6±6.4[*]	1.65±0.3	56.4±4.2	20.7±1.2
Male	8	27.2±2.3	1.74±4.9	69.5±0.6	22.9±1.8
Female + Male	16	28.9±5.0	1.70±0.6	63.0±8.5	21.8±1.9

*Standard deviation; #Body Mass Index = weight (kg) / [height (m)]^2

2.4. Experimental procedure

Before each test, the chamber was preconditioned to the temperature and RH according to Table 1 and the floor fans were turned on at a low speed to create background air movement in the chamber.

Each test took 2 hours, including one adaptation period, three 30-minute test periods, and two short breaks (Fig. 2). The subjects were instructed to adjust their fan speeds freely in the adaptation and sedentary periods, but not during break periods.

At the beginning of each test, the subjects sat for 15 minutes in the chamber to adapt to the environment, while adjusting fan speed to maintain personal comfort. They answered computerized surveys at the beginning and end of this period. The first sedentary test period lasted 30 minutes, during which the subjects worked on their computers. They answered surveys at the middle and end of the period.

The first break (low activity break) was 5 minutes, in which the subjects were asked to turn fans off, stand up and leave their workstations. They were instructed to walk around and stretch their arms and legs, and to take 12 vertical steps with a 22 cm height step stool. This was to simulate activity levels resembling those in offices when occupants are away from their desks (go to coffee machine, printer and etc.). After the exercise the subjects went back to their workstations, answered a survey, turned on their fan, and immediately took a second survey. Another 30 minutes elapsed until the second break, with three surveys.

The second break (high activity break) was 10 minutes. The subjects were asked to turn the fans off again and take four sets of 20 vertical steps to simulate going upstairs and downstairs. After this break the subjects resumed sedentary in their workstations for a final 30 minutes, answered an identical set of survey questions, and left the test chamber.

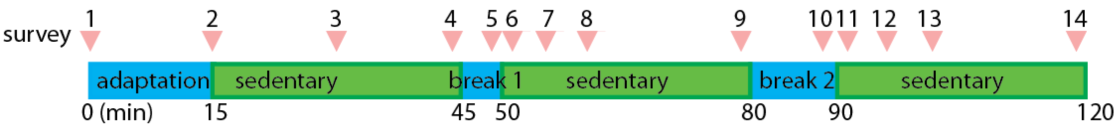
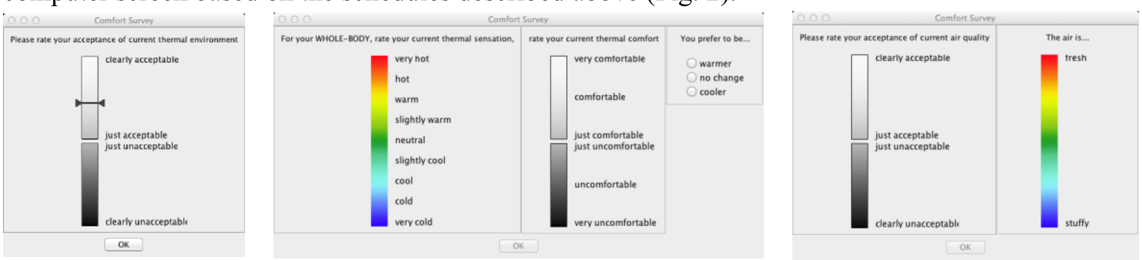


Fig. 2. Experimental procedure.

2.5. Questionnaires

The survey questionnaires include six parts: (1) overall thermal acceptability; (2) thermal sensation (TS) in a 9-point extended ASHRAE scale, thermal comfort (TC) and thermal preference; (3) perceived air quality (PAQ) and air freshness; (4) humidity acceptability and sensation; (5) air movement acceptability (AMA) and preference; and (6) eye-dryness discomfort. All the acceptability, TC, eye-dryness scale, and air freshness scales ranged from -4 to 4. A few examples of the survey questions are shown in the Fig. 3. The survey questions automatically appeared on the subjects' computer screen based on the schedules described above (Fig. 2).



a. thermal acceptability

b. thermal sensation, thermal comfort and preference

c. percieved air quality and air freshness

Fig. 3. Sample survey screens.

2.6. Statistical analysis

The statistical analysis was performed using Graphpad 6 Prism (Graphpad, San Diego, CA) with repeated-measure Friedman test with Dunn's post-hoc test. Statistical significance was tested at $p<0.05$.

3. Results

3.1. Indoor physical environment

The indoor temperature and RH were controlled close to the planned conditions (Table 4) in the tests. The indoor CO_2 level was 200 ppm above that of the outdoors during sedentary periods, and went up to 300 ppm higher during elevated activity periods. This means that the air quality in the chamber was good.

Table 4 Planned and measured temperature and RH

Planned		Measured（mean over 4 WSs）	
T (°C)	RH (%)	T (°C)	RH (%)
26	60	25.97±0.17	61.9±0.8
26	80	25.86±0.27	78.3±0.8
28	60	27.99±0.07	61.5±0.6
28	80	27.86±0.13	78.7±0.7
30	60	29.84±0.07	61.9±0.6
30	80	30.01±0.16	77.4±0.7

3.2. Subjective responses

3.2.1 Responses over time

Fig. 4 displays mean overall TS, TC and PAQ over time for the entire experiment. The subjects' mean TS in each sedentary period were between neutral to slightly warm in all test conditions except 30°C and 80% RH. The TS votes were slightly higher at the beginning of adaptation periods, and reached stable levels within 30 minutes (Fig. 4a). At the end of the first break, TS increased 0.5 scale units in condition 1, 4 and 5; and increased nearly 1 scale unit at the condition 2, 3 and 6. Turning on the fan after the break 1 significantly decreased TS to neutral levels. TS reached stable levels within 5 minutes in the second sedentary period. The second break increased TS from the last sedentary votes by 1 to 1.5 scale units, to the "warm" or "hot" side. Again, TS decreased immediately after turning on the fan, and reached previous levels within 5 minutes.

The subjects were thermally comfortable and acceptable with the air quality in all test conditions except at the beginning of adaptation periods and after the two breaks (Fig. 4b, 4c). Similar patterns were found for the TC and PAQ votes. The TC and PAQ votes were lower at the beginning of the tests, and improved by air movement over time in the first 45 minutes. The two high activities breaks decreased the TC and PAQ levels significantly; when exposed to air movement after the breaks, TC and PAQ were improved immediately and were completely restored within 5 minutes.

In all test conditions, no significant differences were found between the 3 last votes for TS, TC and PAQ in any of the three 30-minute sedentary sessions, indicating that the adaptation period and the two high activities breaks have no significant effect on the subjects' votes after they had been exposed to personally controlled air movement for 30 minutes.

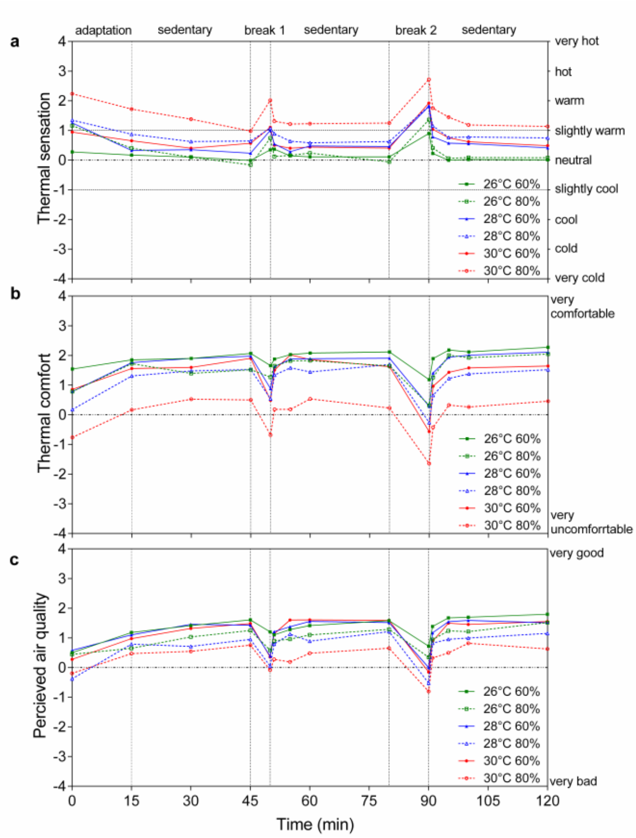


Fig. 4. Mean overall thermal sensation, thermal comfort, and PAQ votes over time

3.2.2 Steady-state responses

As mentioned before, pre-conditions (adaptation and high activity breaks) had no significant effect on the subjects' votes once stability was reached, and therefore the last votes of each sedentary period were pooled and analyzed as steady state responses.

3.2.2.1 Thermal sensation, thermal comfort and thermal preference

Fig. 5a shows the boxplot of TS votes at the six test conditions. The median TS votes were almost 0 at 26°C 60% and 80% RH; the distribution is well within ±1, indicating that almost all the votes are neutral. For the test conditions 2, 3, and 4, more than 75% percent of the TS votes were in the neutral range, with median TS at 0.2, 0.52 and 0.49 respectively. The test condition 6 is the only condition with significantly higher votes than the rest of the test conditions ($P<0.001$), with about 50% of TS votes above 1.

The TC responses (Fig. 5b) shows that comfort was well maintained in test conditions 1 to 5, with nearly 100% of the subjects were comfortable in conditions 1 to 3, and more than 80% in conditions 4 and 5. In condition 6, only 60% of the subjects reported being comfortable.

The TP votes show that over 60% of the subjects wanted "no change" in test conditions 1 to 5, and 40% in test 6 (Fig. 5c). However, more than 20% of the subjects wanted to be "cooler" in test conditions 3, 4, 5, and nearly 60% of subjects in test 6.

Fig. 5 shows significant effects of humidity on TS, TC and preference votes at higher temperatures

(28ºC and 30ºC), which were associated with higher TS votes, lower TC votes and a larger percentage of the subjects wanting to be "cooler".

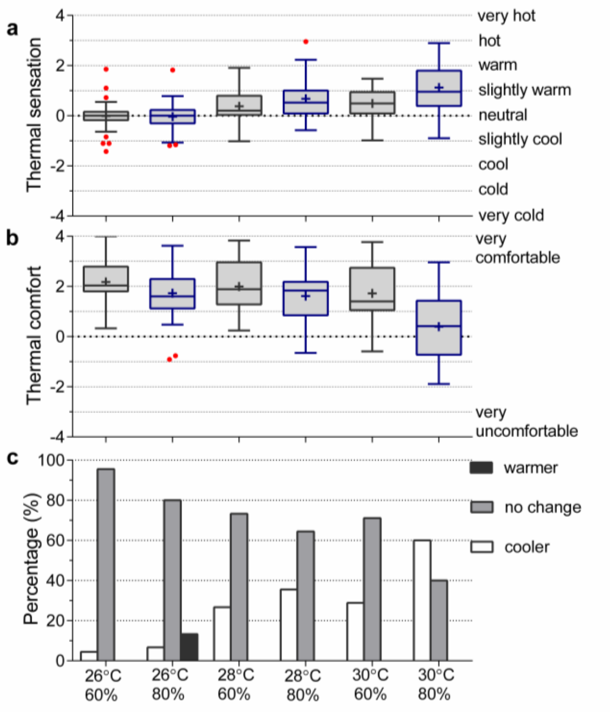


Fig. 5. Thermal sensation, thermal comfort and thermal preference votes at each test condition. The figure shows median votes (lines), 25% to 75% quartiles (boxes) and ranges (whiskers). Mean votes are shown as crosses. Red dots are shown if extreme values are more than 1.5 times the interquartile range of the box.

3.2.2.2 PAQ and air freshness votes

The PAQ votes were similar among test conditions 1 to 5 (Fig. 6a). The acceptability for test condition 6 was significantly lower than the other conditions ($P<0.001$), but was still within the acceptable range. However, more than 20% of the subjects perceived the air to be stuffy in all the test conditions (Fig. 6b). At the test conditions 4 and 6, nearly 75% of the subjects perceived the air stuffy. Nonetheless, the subjects reported acceptable PAQ, which suggests that providing air movement may maintain acceptability of PAQ, but may not make the air feel fresh. Post-hoc analysis shows that freshness votes were lower at 80% RH than 60% RH at 28 ºC and 30 ºC ($P<0.001$), and lower at 28 ºC 80% RH than 30 ºC 60% RH ($P<0.001$). The subjects may have felt the air stuffy, despite the high fresh air supply rate in the chamber, because they were tested in a chamber with fixed windows. Also, the outdoor conditions during the test period were cool and dry rather than hot and humid. Further study in a hot-humid outdoor climate may be needed to determine this effect.

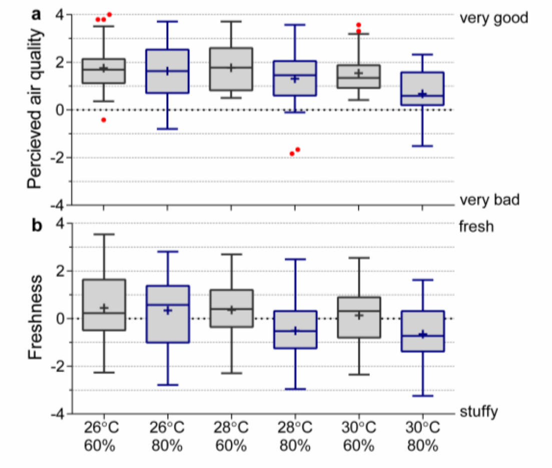


Fig. 6. PAQ and air freshness votes. See Fig. 5 definition of symbols.

3.2.2.3 Fan usage, air movement acceptability and preference

During all the tests the fan power for each WS was continuously measured. The measured fan power was continuously converted to fan speed levels. The air speed levels in the last 5 minutes during each sedentary session were selected to represent steady-state speed levels. The measured air speeds at the 1.1m heights were used in the current analysis. Fig. 7 shows the air speed selected by the subjects under 6 test conditions (Fig 7a), and the corresponding fan power (Fig. 7b). The selected mean air speed was 1.3m/s at 30°C and 80% RH, 1 m/s at 30°C/60% RH, 0.7 m/s at 28°C/60% RH and 80% RH, and 0.4 m/s and 0.3 m/s at 26°C/80% RH and 26°C/60% RH respectively. The mean energy consumption based on the selected speed was 3W to 10W. There were big individual differences among the subjects. Some preferred high air speed even when they felt cool, while some preferred no air movement even when they felt hot and uncomfortable.

Fig. 8a shows that the distribution of the subjects' air movement acceptability votes was on the acceptable side, with nearly 75% votes at test condition 1 to 5 higher than 1 on the scale. There were no significant differences between test conditions 1 to 5. Only the test condition 6 was significantly lower than other test conditions ($p<0.0001$), however the majority of the votes were still on the acceptable side (89%).

Most of the subjects (more than 60%) indicated "no change" as their preference for air movement, in all the test conditions except in the test condition 6 (50%) (Fig.8b). More subjects preferred "more" air movement rather than "less" in all test conditions except in test condition 2. Further analysis shows that only 10% of the subjects who wanted more air movement actually used the full power of their fan. For those subjects who didn't choose full power, the reason may be that the control of fan speeds was not step-less, thus some subjects chose a lower air speed than needed because the next speed level was considered too high for them. The 10% of subjects who wanted more air movement even while using the full power of their fans (all at 30°C and 80% RH) did not have sufficient air speed for this test condition. This information could be useful for the design and implementation of floor fans on adding more air speed control options and increasing the maximum air speed for environments with higher temperature and humidity.

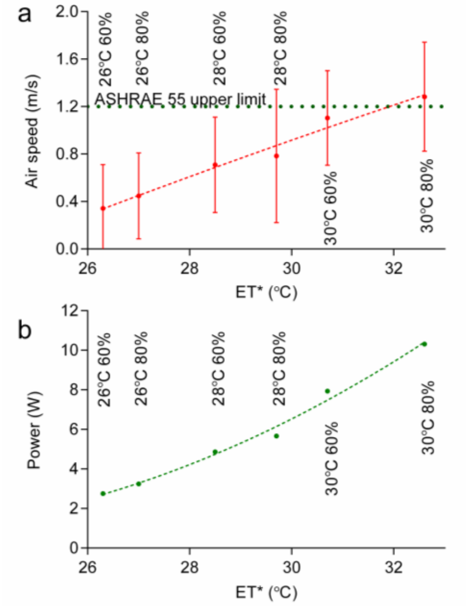


Fig. 7. Air speeds selected by the subjects, and corresponding fan power

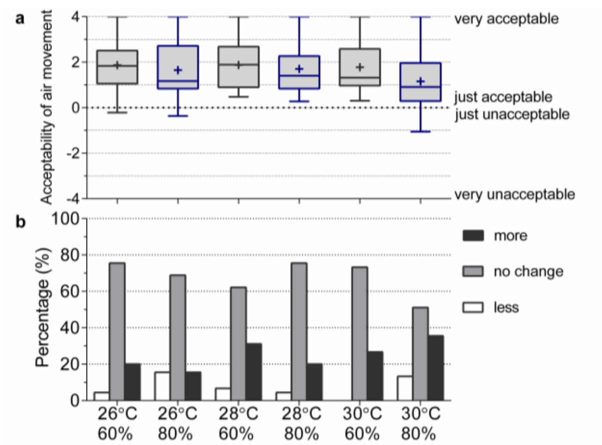


Fig. 8. Acceptability and preference of air movement. See Fig. 5 definition of symbols

3.2.2.4 Humidity acceptability and humidity sensation

Humidity acceptability votes were comparable among the test conditions 1 to 5, while in test condition 6 they were significantly lower (P<0.001), with nearly 40% of the subjects reporting unacceptable (Fig. 9a). The median humidity sensation votes were similar for the test conditions 1 to 5, with the subjects' humidity sensation votes evenly distributed around neutral. At 30 ºC and 80% RH, 75% of the subjects sensed the air as humid (Fig. 9b); this may explain the low acceptability of humidity at this test condition..

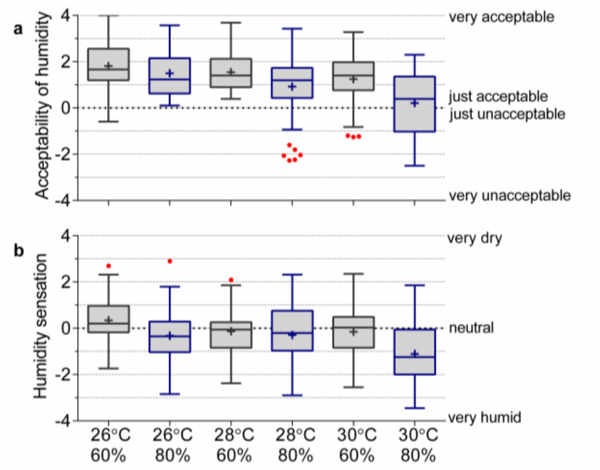


Fig. 9. Acceptability of humidity and humidity sensation. See Fig. 5 definition of symbols.

3.2.2.5 Eye-dryness discomfort

The distributions of Eye-dryness acceptability were mainly on the acceptable side at all tests conditions. No significant differences were found (P = 0.2895) among all the test conditions despite the high air speed chosen by the subjects, indicating that the elevated air speed controlled by the subjects did not cause eye-dryness discomfort in these warm-humid environments (Fig. 10).

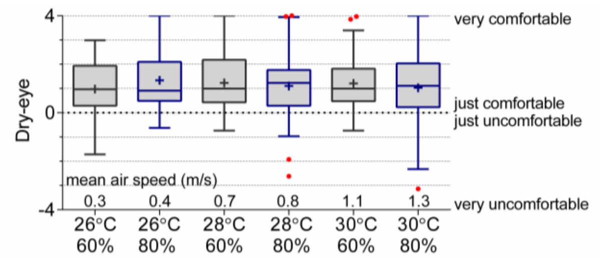


Fig. 10. Eye-dryness discomfort. See Fig. 5 definition of symbols.

3.2.2.6 The acceptability threshold

Fig. 11 shows the percentage acceptable (PA) with overall thermal environment, air quality, air movement and humidity. The PA only decreased at 30ºC and 80% RH (32.7ºC ET*). The PA of air quality and air movement was above 80% for all test conditions. The PA of overall thermal environment and humidity was higher than 80% in all conditions except 30ºC and 80% RH, suggesting an upper limit at 30ºC and 60% RH for cooling with such horizontal fans.

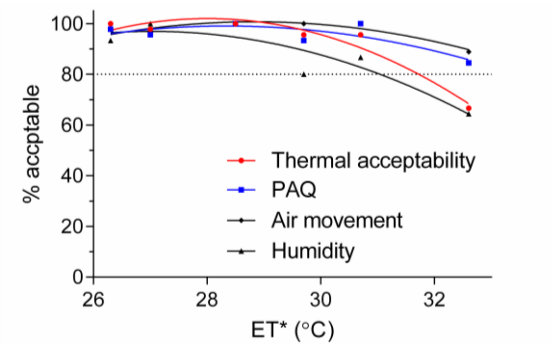


Fig. 11. Percentage acceptable with overall thermal environment, PAQ, air movement and humidity

4. Discussion

4.1. Comparison with the ASHRAE comfort zone with elevated air movement

ASHRAE Standard 55 2010 specifies the air movement required to compensate for elevated temperatures above the standard's summer comfort envelope, for both with and without occupant control over air movement. With occupant control, ASHRAE 55 specifies a comfort zone with elevated air movement up to 1.2 m/s. To compare our results with this comfort zone, we calculated equal SET curves for 60% and 80% RH respectively based on the method provided by ASHRAE 55 (Fig. 12). The air speeds chosen by the subjects for this study's temperature-humidity combinations are plotted on the same chart for comparison. It can be seen that, at 26°C and 28°C, the study's results are well within the ASHRAE comfort zone, however at 30°C/60RH, most subjects chose higher air speed than 1.2m/s. At 30°C /80% RH, most subjects again chose higher air speeds but this time some of them were not able to be comfortable. These results suggest that at temperatures near 28 and 30°C air speeds of 1.8 m/s are practical, but may not be sufficient for the combination of 30°C /80% RH.

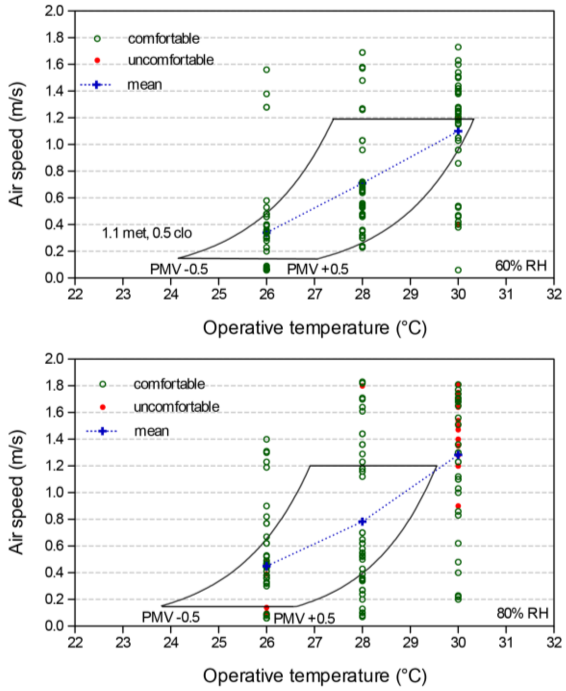


Fig. 12. Comfortable temperature, RH and selected air speeds against the ASHRAE comfort zone at 60% and 80% RH with elevated air movement. The calculations were made with 0.5 clo and 1.1 met

4.2. Comparison with previous studies

The present results confirm previously findings that personally controlled air movement can maintain thermal comfort in warm-humid environments [18][19]. The mean TS votes in the current study were mostly within the neutral to slightly-warm range at 28ºC and 30ºC (see Fig.5a), while in study [18] and [19], the subjects' TS were mostly on neutral to slightly cool range. The reasons may be that we used commercially available fans instead of fan-boxes producing air speed over a larger area of the body, and their subjects preferred slightly higher air speeds than our fans were capable of providing.

Arens et al. [23] described the effect of air movement on restoring thermal comfort and PAQ at 28 ºC and 50% RH after breaks with high levels of activity. Our study extended their findings to higher humidity at 28ºC and 80%RH, and higher temperature at 30ºC and 60% RH, showing that air movement can restore comfort immediately after turning on the fan after a 12-step break, and that thermal comfort and PAQ were improved immediately after a 80-step break, and were restored within 5 minutes. Because air movement can improve comfort so quickly, it can be combined with more slowly acting systems, such as radiant cooling systems, to improve comfort and to save energy by reducing the number pre-cooling hours.

Another important finding of the current study is that PAQ was well maintained by elevated air movement at temperature-humidity combinations up to 30ºC and 80% RH, with less than 20% of the subjects dissatisfied with PAQ. This finding confirmed previous findings of Zhang et al. [17], Arens et al. [22-23] and Melikov et. al. [24-26], and extended the positive effect of air movement on PAQ to higher temperatures and humidity.

The present study shows that the high air speeds chosen by the subjects didn't cause eye dryness discomfort in warm-humid environments. This confirmed previous findings by Melikov et al.[29], which suggested that in warm-humid environment the water evaporation due to elevated air speed was low, and that giving subjects personal control over air speed might act to reduce eye dryness discomfort.

The mean power required to maintain a subject's comfort with the floor fan was only 10W at 30ºC 60% RH, a very energy-efficient way for providing comfort in buildings. In air-conditioned buildings, less cooling is required with the raised temperature and humidity set points permitted by elevated air movement. Air movement saves further energy by increasing the number of days in which natural ventilation or economizer cycles can be comfortably employed [30][31].

Human performance was not addressed in the current study. It is suggested by Wyon that the thermal state of the body determines arousal thus also performance [32], therefore warm temperatures may reduce performance by inducing warm sensations [33-34]. Since air movement can offset warm temperatures and maintains occupants' thermal state close to neutral, it may maintain performance close to that at neutral temperatures. This is supported by study [17] and [35], in which isothermal airflow was found to maintain performance at temperatures up to 30ºC. It is worth to note that parameters other than temperature and air movement may also affect performance, such as humidity, air movement characteristics, ventilation rates, pollution levels, further studies should be done to address this.

Several limitations of the current study should be addressed. Only 16 subjects participated the current experiment. And the subjects were not acclimated to hot-humid climate. The chamber was ventilated with large amount of outdoor air, which is not always the case in real buildings. Further studies with more subjects who are acclimated to a hot-humid climate should be done to validate the findings of the current study, and the effects of different ventilation rates should be studied as well.

5. Conclusions

In conclusion,

1. Thermal comfort can be maintained up to 30ºC and 60% RH, and PAQ could be maintained up to 30ºC and 80% RH with personally controlled air movement, without causing discomfort from humidity, air movement or eye dryness;
2. Thermal comfort and PAQ could be restored immediately after turning on the fans after the low

activity breaks, and comfort and PAQ were improved immediately after turning on the fans after the high activity breaks and restored within 5 minutes;

3. The 80% acceptable limit can be extended to 30ºC and 60% RH with personally controlled air movement;
4. The power required for maintaining comfort with the floor fan was less than 10W per person, which is a very efficient way to reduce energy consumption in hot-humid climate.

Acknowledgements

The work was supported by National Natural Science Foundation of China (Project No. 50978102, 50838003), California EPA Air Resource Board (Project No. 10308), Center for the Built Environment, UC Berkeley, Program for New Century Excellent Talents in University, and National Key Technology R&D Program of China (Project No. 2011BAJ01B01). The authors would like to thank Professor Shin-ichi Tanabe for kindly helping us on purchasing and shipping the floor fans.

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