Enabling Energy-Efficient Approaches to Thermal Comfort Using Room Air Motion

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Abstract

Moving air cools human body. In warm environments, fans can provide comfort using less energy than air-conditioning. The savings in HVAC energy is substantial, and greater if fans enable buildings to be successfully conditioned by natural ventilation or evaporative cooling systems, instead of chillers. Although there are many laboratory studies for desk fans and personalized fans, the tests for ceiling fans are rare, mainly from early studies in 1980s. The purpose of this study is to examine cooling effect of an integrated low-wattage ceiling fan on people in warm environments when air comes from different directions with different speeds. We conducted 96 human subject tests in an environmental chamber. Sixteen college students each experienced 6 air movement conditions: two different air speeds and three different air directions from the fan toward the subject-from front, side, or right above the head. The difference in thermal comfort and thermal sensation generated by fixed and oscillating fans was also investigated. The temperature and humidity conditions for the tests were 28 °C and 50% RH. The two air velocities were selected based on previous experiments conducted with human subjects in our environmental chamber. The two hour test schedule included two five minute breaks when subjects were asked to be away from the fans, simulating conditions in real offices when people are away from fans.

Subjective responses about thermal sensation, comfort, temperature satisfaction, perceived air quality, and preferred air movement were obtained periodically during the test, including the break periods. The results show that the ceiling fan is capable of providing thermal comfort under the tested warm condition.

Keywords - Integrated ceiling fan; Air movement; Thermal comfort; Thermal sensation; Oscillating airflow.

1. Introduction

The amount of energy used to condition commercial buildings is increased by the tendency of building operators to maintain buildings at too-low ambient temperatures during warm seasons [1]. The overcooling was found to significantly reduce occupant comfort and even caused health symptoms [2]. There are a number of reasons for summer overcooling, but an important one is the insufficient air movement around occupants in conventional sealed office buildings [3], [4]. Sealed designs with low air movement consistently show lower occupant satisfaction than offices with operable windows [5], [6]. Although buildings with operable windows tend to have warmer interior temperatures than sealed buildings, the modest increase in indoor air movement that they provide gives them comfort ratings superior to those of sealed buildings.

This suggests one can reduce cooling energy demand by allowing a building to float within an expanded indoor temperature range while maintaining the occupants' thermal comfort by providing air movement using fans. Fans of very low wattage (as low as 3W) have been shown to yield the equivalent of 3K (6ºF) offset of air temperature within an individual workstation [7]. Buildings employing such fan cooling promise substantial savings in their HVAC energy, more than 30% below that of conventionally conditioned buildings [8]. The energy savings may be even greater if the warmer setpoint temperatures enable the primary cooling source to be switched from a compressor-based system to one of the more efficient and lower-power approaches, such as natural ventilation, evaporative cooling, or radiant ceiling/floor systems. Room fans may be readily applied in both new and retrofit designs since they can be easily installed and the savings can be achieved by only changing HVAC system setpoints.

The challenge is how to implement indoor air movement devices within the interior space, so that they are: highly energy efficient, comfortable and acceptable to occupants, visually attractive to building management and designers, and straightforward to design. For this study we integrated a head of a floor fan into a ceiling panel. The fan can oscillate. The purpose of this study is to characterize the thermal feeling related with the use of this ceiling fan, with different subject-fan positions, different air velocities, and fixed vs. oscillating fan setting.

2. Method

The experiments were carried out at the Center for the Built Environment (CBE), University of California at Berkeley, between August and September 2012.

Chamber setup and the ceiling fan

We set up 4 workstations in the chamber (Fig. 1) with two fans. One fan was set in a way to provide airflow toward heads and faces of the two subjects' (we call it "front" in the paper). The other fan provided airflow towards sides of faces of the two subjects' (we call in "side" in this paper).

The two prototypes of oscillating ceiling fan were made (Fig. 1 Chamber set up and ceiling fan prototype). Fan motor and propeller are commercially available, while the structure to integrate the fan into ceiling panels was made for this scope. The fans are very energy efficient, with an energy consumption that ranges from 2 W to 15 W.

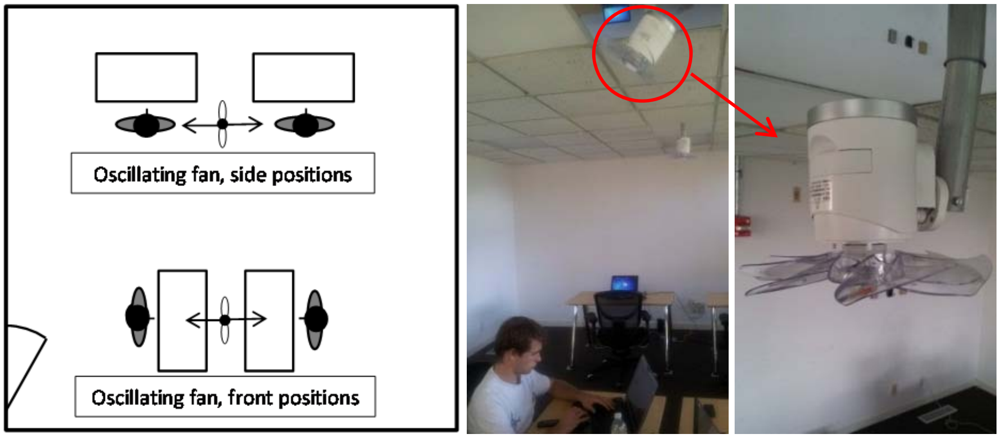


Fig. 1 Chamber set up and ceiling fan prototype

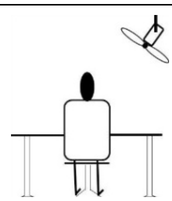
The fan power can be set among 7 levels. For this study we selected level 2 and level 3. The fan oscillation period is 28 seconds.

Subjects and test conditions

Human subject were tested to evaluate comfort for warm conditions (28 °C). The relative humidity of the chamber was kept at 50% ±1%.

Several configuration were studied, the subjects experienced two different air velocity and three different air directions, plus the oscillation feature. A schematic representation of all the different configurations and their configuration codes used in the analysis is presented in Table 1.

Table 1 test configurations

Subject position	Fan mode	Power level	Configuration code
 Front	Fix	2	2 Fix Front
		3	3 Fix Front
	Oscillating	2	2 Oscillating Front
		3	3 Oscillating Front
 Side	Fix	2	2 Fix Side
		3	3 Fix Side
	Oscillating	2	2 Oscillating Side
		3	3 Oscillating Side
 Below	Fix	2	2 Fix Below
		3	3 Fix Below

Sixteen subjects (8 females and 8 males) participated in each of the ten test conditions, plus one test without fans, for a total of 112 tests. The tests without fan (in this paper called no-fan) provided reference conditions for comparison with the tests with the fans.

Subjects were asked to wear summer clothing (0.5 clo).

Schedule for the tests

Each test took one hour and forty-five minutes. At the beginning of the test, the subjects sat for 15 minutes in a room outside the chamber (≈ 21 °C), to stabilize their metabolic levels. After these 15 minutes the subjects moved into the environmental chamber and sat at the workstations with the fans on. The remaining part of the test was divided into three parts by two five minute breaks. The first part, 20 minute long, was used to let subjects' body adapt to the temperature. The second and the third part are 30 minutes long. The results from part 2 and 3 are used for the analysis. During the breaks the subjects were asked to stand up, and in the middle of each break period, they took 12 vertical steps on a 22cm tall step stool. This was to simulate activity levels when occupants are away from their desks in a real office. After the second break we asked the 2 subjects experiencing "front" airflow to switch workstations with the 2 subjects experiencing "side" airflow, to test different fan oscillating directions.

The survey questions automatically appeared on subjects' computer screens based on pre-set schedules (Fig. 2).

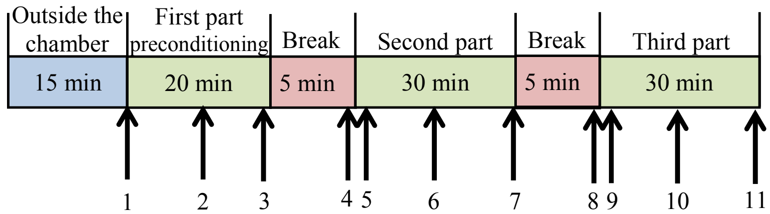


Fig. 2 Test schedule. Arrows indicate times when the survey are administrated

Survey questions

In addition to temperature satisfaction, thermal sensation, preferred thermal sensation, and thermal comfort (for the whole body and several body parts separately), the survey questionnaire also included questions related with the use of fans: air movement acceptability, air movement preference, and dry-eyes discomfort. We also included two questions about air quality acceptability and air freshness, to investigate the effect of air movement on perceived air quality.

Two survey question examples are shown in Fig. 3. The scales are continuous.

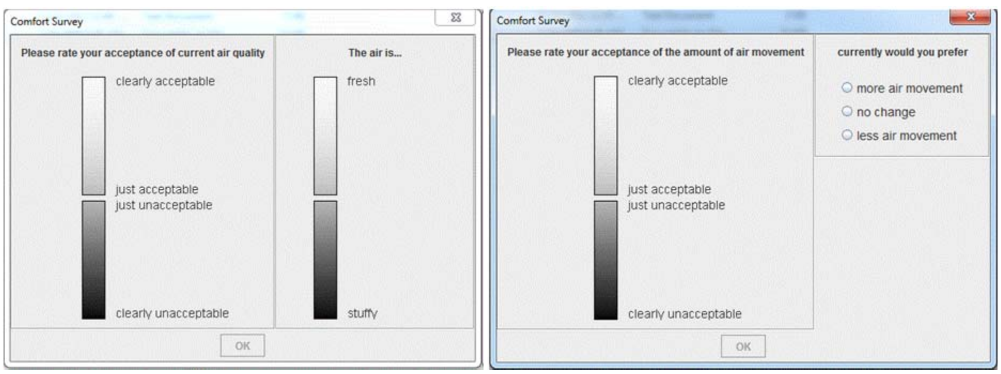


Fig. 3 Two examples of survey questions

Measurements

Room air temperature and humidity were measured at 1.1 m height.

Air velocity was measured for all the configurations in 27 points in the area where the subjects were supposed to be sat at 4 heights. In this paper only the air velocity values at three heights (1.1 m, 0.6 m, and 0.1m), and at the location 20 cm from the center of a desk, are reported (see Table 2).

Table 2 Measured air velocities and standard deviation

Configuration code	Mean value [m/s]/SD[m/s]		
	1.1 m	0.6 m	0.1 m
2 Fix Front	0.68/0.16	0.51/0.11	0.24/0.06
3 Fix Front	0.88/0.13	0.62/0.12	0.28/0.07
2 Fix Side	0.70/0.21	0.76/0.11	0.34/0.09
3 Fix Side	0.81/0.29	0.79/0.48	0.35/0.19
2 Fix Below	0.66/0.20	0.54/0.25	0.24/0.12
3 Fix Below	0.88/0.49	0.69/0.27	0.31/0.11

Air speed was measured with omnidirectional hotwire anemometers, with a response time of 2s and an accuracy of 0.02m/s±1.5% of reading

3. Results

This paper focuses on stable conditions, analyzing subjects' responses to the number seven and eleven surveys (see Fig. 2), and leaving the results of the other surveys for future analysis.

Whole-body thermal sensation and thermal comfort

In the following analysis every graph is followed by a table representing results of statistical analysis. In the tables symbol X represents a statistically significant difference between two test conditions ($p<0.05$). All the results for the configurations with fans were compared with the reference condition, no- fan. The statistical analysis was performed with a non-parametric method called permutation test, using the program NPC Test R10. For more details about the program and the non-parametric method used, please see [9].

In

Fig. 4 the whole body thermal sensations are presented for the eleven configurations. Based on the results presented in Table 3, there are no differences between "no-fan" and the "oscillating fan" configurations. The differences are statistically significant between "no-fan" and the two configurations (front and side) with fix fans set at velocity level 3.

Almost the same results were obtained for the whole body thermal comfort (Fig. 5, Table 3). In this case, in addition to the two fixed-fan velocity level 3 configurations, the test condition "3Fix Below" also presented a statistically significant difference compare with "no-fan" configuration.

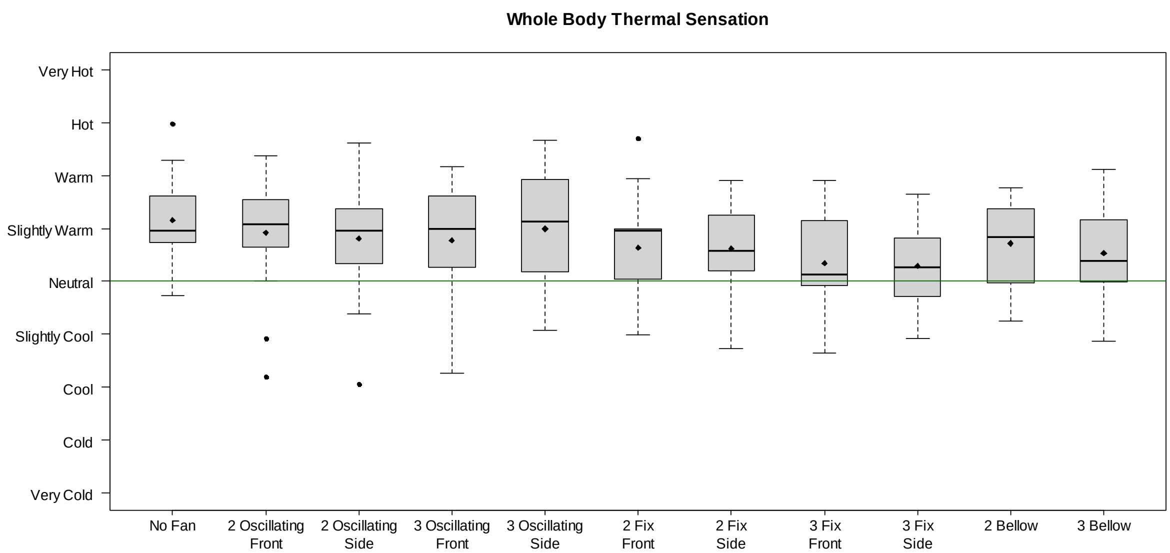


Fig. 4 Whole body thermal sensations

Table 3 Whole body thermal sensation statistical analysis

Whole body thermal sensation	2 Oscill. Front	2 Oscill. Side	3 Oscill. Front	3 Oscill. Side	2 Fix Front	2 Fix Side	3 Fix Front	3 Fix Side	2 Fix Below	3 Fix Below
No-Fan							X	X		

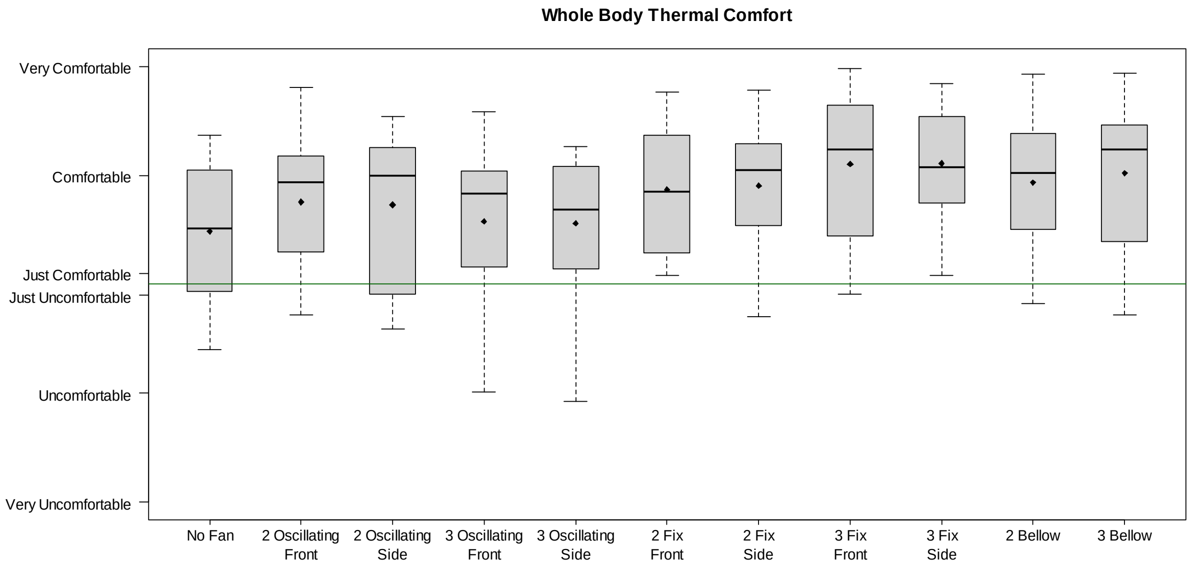


Fig. 5 Whole body thermal comfort

Table 4 Whole body thermal comfort statistical analysis

Whole body thermal comfort	2 Oscill. Front	2 Oscill. Side	3 Oscill. Front	3 Oscill. Side	2 Fix Front	2 Fix Side	3 Fix Front	3 Fix Side	2 Fix Below	3 Fix Below
No-Fan							X	X		X

Air quality acceptability

Air quality acceptability is reported in Fig. 6. The statistical analysis presented in Table 5 shows that almost all the configuration with fan (except the two velocity level 3 oscillating-fan configurations) performed better in terms of air quality acceptability compare to the configuration without fan.

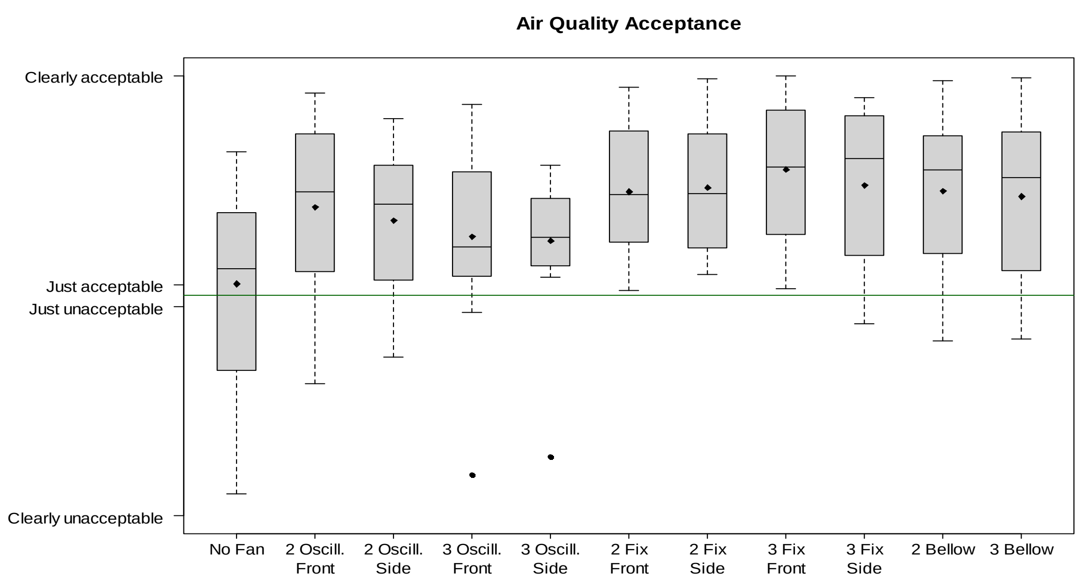


Fig. 6 Air quality acceptance

Table 5 Air quality acceptability statistical analysis

Perceived air freshness	2 Oscill. Front	2 Oscill. Side	3 Oscill. Front	3 Oscill. Side	2 Fix Front	2 Fix Side	3 Fix Front	3 Fix Side	2 Fix Below	3 Fix Below
No-fan	X	X			X	X	X	X	X	X

Air movement preference

Subjects were asked about their preferences for the amount of air movement. They had to choose among three options: 1) less air movement; 2) no change; 3) more air movement. Results are presented in Table 6.

As expected, for the configuration without fans, the majority of the subjects (94%) wanted more air movement. For oscillating-fan, more people would like to have more air movement. For fixed-fan, more people would like to have less air movement.

Table 6 Air movement preferences

Fan Configuration	Less air movement	No change	More air movement
no-fan		6%	94%
2 Oscillating Face		56%	44%
2 Oscillating Side		44%	56%
3 Oscillating face		44%	56%
3 Oscillating Side		38%	63%
2 Fixed Front	13%	50%	38%
3 Fixed Front		75%	25%
2 Fixed Side		56%	44%
3 Fixed Side	19%	56%	25%
2 Above	6%	50%	44%
3 Above	13%	56%	31%

Dry Eyes Discomfort

One of the survey questions was to investigate dry eyes discomfort. No dry eyes discomfort was detected for anyone of the eleven configurations.

4. Discussion

1) Comparing to no-fan reference configuration, neither the whole body thermal sensation nor the whole body thermal comfort seems to be affected by the oscillating-fan. The reason could be due to the long oscillation period. The interval of time during which there is no air movement provided by the fan was too long compared to relatively short period when air movement was provided. The configurations with the fix fan set at velocity three showed an improved thermal comfort and a cooler whole body thermal sensation. The p-values for all the others configurations with fixed-fan were very close to the level of significance, fixed at 0.05. Probably a bigger sample size would have been able to detect a statistically significant difference between the "no-fan" case and the "2fix"-"2 and 3 below" configurations.
2) Almost all the configurations performed better than the reference configuration in terms of air quality acceptability. This is interesting especially because the cases with oscillating-fan did not have statistically significant influence on whole body thermal sensation and thermal comfort. From these results it seems that simply having a certain amount of air movement may improve air quality perception.
3) There is no statistical difference between front and side oscillating-fan configurations.
4) In terms of "air movement preference" the configuration "3 fix front" performed the best (biggest "no change" population, 75%). Under this condition, for an average air velocity around 0.9 m/s, nobody asked for less air movement.
5) The combinations of air velocities, air directions, temperature and humidity tested in this study did not cause any appreciable dry eyes discomfort. A ceiling fan blowing air at about 0.9 m/s from front, side, or directly above towards subjects' head didn't cause dry eyes discomfort.

5. Conclusions

1) The oscillating-fan tested in this study had no statistically significant effect on subjects' thermal comfort and thermal sensation. Further study is needed to understand reasons, whether the ineffective is due to the fan settings or due to psychological feeling.
2) Under the tested conditions, a fixed-fan that directs air over a human body at a velocity between 0.8 and 0.9 m/s has a positive and statistically significant effect on users' thermal comfort and thermal sensation.
3) Air quality acceptability is improved by the air movement, even if the amount of air movement is not enough to improve subjects' thermal comfort and thermal sensation.
4) For the ceiling fans studied in this work, an air velocity of 0.9 m/s directed on subjects' face did not cause any dry eyes discomfort.

6. Acknowledgment

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7. References

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