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

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## Abstract

In warm environments, room fans can provide comfort using substantially less energy than air-conditioning. The savings are greater if the fans make it possible to successfully condition the building with natural ventilation or evaporative cooling systems, instead of chillers. Although there are many laboratory studies of comfort using desk fans and personalized fans, tests for ceiling fans are rare, mainly in early studies from the 1980s. This study examines the cooling effect of a low-wattage ceiling fan on occupants 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 between fan and subject: from front, side, or right above the head (total eleven configurations). 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.

It was found that the majority of subject (70%) perceive the thermal environment without fans comfortable. This number rise to 100% for some configuration with fans. Our subject found that the oscillating air movement had no effect in terms of improved thermal comfort or thermal sensation, but it greatly improves their air quality perception. The subjects did not report any dry eyes discomfort for any of the eleven configurations.

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

## 1. Introduction

Compressor-based air-conditioning is the second largest consumer of electricity in US commercial buildings, exceeded only by electrical lighting (141 billion kWh vs. 393 billion kWh), [1]. In office buildings compressor-based cooling constitutes roughly 15% of total electricity consumption.

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 [2]. The overcooling was found to significantly reduce occupant comfort and even caused health symptoms [3]. 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 [4,5]. Sealed designs with low air movement consistently show lower occupant satisfaction than offices with operable windows [6,7]. 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 offset of air temperature within an individual workstation [8]. Buildings employing such fan cooling promise substantial savings in their heating, ventilation, and air conditioning (HVAC) energy, more than 30% below that of conventionally conditioned buildings [9-11]. 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 or evaporative cooling. 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.

Since the 1960's, the use of air movement to maintain thermal comfort in warm conditions was impeded by strict limits to air movements in thermal comfort standards (e.g. ASHRAE 55-1992, 2004 and ISO 7730). This has led to almost no innovation in designing interiors to use air movement, and only modest innovation in industrial products that move air. However, in recent years, the air movement requirements in

these standards have been revised to permit higher indoor air speeds, following the results of extensive field and laboratory studies (ASHRAE 55-2010 [12]). The revisions pave the way for the above mentioned 30% reduction in HVAC, and also for significant reduction in their peak power demand. They also enable more individual environmental control and the good levels of occupant comfort already observed in naturally ventilated buildings with fans in warm and humid climates [9,13-17].

The ASHRAE database of comfort field studies [4,5,18,19] shows that more occupants prefer more air movement, while very few prefer less, when environments are in the range of slightly cool to slightly warm. The challenge becomes 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 purpose we integrated a head of an oscillating floor fan into an acoustical ceiling panel, and performed this study to characterize the thermal responses of occupants under different subject-fan positions, different air velocities, and fixed vs. oscillating fan settings. This is just a first step toward a new generation of ceiling integrated fans that can satisfy users' demand for comfort and reduce building energy consumption. This study proves the effectiveness of these devices and lets industry to move the next steps, especially for what concern a visually attractive design that would facilitate the use of fans in offices.

Another objective of this study is to investigate the effect of an intermittent air movement on subjects' thermal comfort and thermal sensation. There are no examples in literature of studies that considered this type of air flow.

## **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.

## 2.1 Chamber setup and the ceiling fan

We set up 4 workstations in the chamber (Figure 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 this paper). The other fan provided airflow towards sides of heads of the two subjects' (we call it "side" in this paper).



**Figure 1** Chamber set up and ceiling fan prototype

For this study two prototypes of oscillating ceiling fan were made (circled in red in Figure 1). The fan motor and propeller are commercially available, while the structure to integrate the fan into the ceiling panels was custom fabricated. These fans were selected due to their excellent energy efficiency, with an energy consumption that ranges from 2 W to 15 W, and because they are extremely quiet. No difference in terms of dBA were measured with the chamber ventilation system turned on between fan on and off. The average noise level was always around 33 dBA.

The fan power can be set among 7 levels. The oscillation angle is 90°, and the fan oscillation period is 28 seconds.


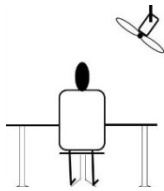

## 2.2 Subjects and test conditions

Human subjects were tested to evaluate comfort for warm conditions ( $28 \pm 0.3^\circ\text{C}$ ). The relative humidity of the chamber was kept at  $50\% \pm 1\%$ .

Four workstations were installed in the Controlled Environmental Chamber at UC Berkeley so that four subjects could be tested at the same time. The chamber size is 5.5 x 5.5 m, with windows on two sides, south and west. The windows are well shaded by fixed external shades. The windows temperature was controlled by a dedicated air system. The room air temperature is controlled by 8 floor grille diffusers, and the air is exhausted through a 0.6 x 0.6 m ceiling return grille.

Several configurations 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 [W]	Configuration code	Test number
 Front	Fan not in use		No-fan	1
	Fixed	2	2 Fixed Front	2
		3	3 Fixed Front	3
	Oscillating	2	2 Oscillating Front	4
		3	3 Oscillating Front	5
 Side	Fixed	2	2 Fixed Side	2
		3	3 Fixed Side	3
	Oscillating	2	2 Oscillating Side	4
		3	3 Oscillating Side	5
	 Below	Fixed	2	2 Fixed Below
3			3 Fixed Below	7

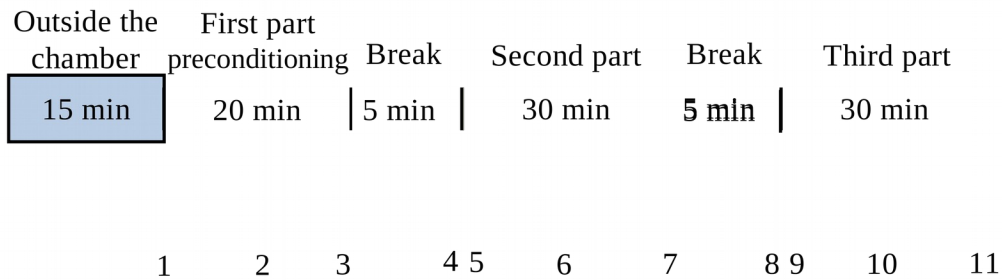
Sixteen subjects (8 females and 8 males) participated in each of the ten test conditions, plus one test without fans. During a single test the subjects experienced two different configurations, one in the first part of the test and one in the second, except for the configurations “2 Fixed Below”, “3 Fixed Below” and “No-fan”, which were tested singly. See the column “Test number” in Table 1. When two configurations have the same test number means that they were tested during the same session. The total number of tests was 112. 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), and their clothing were checked before every test to guarantee the right clo value.

### 2.3 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 ( $\approx 21$  °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 (Figure 1).

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

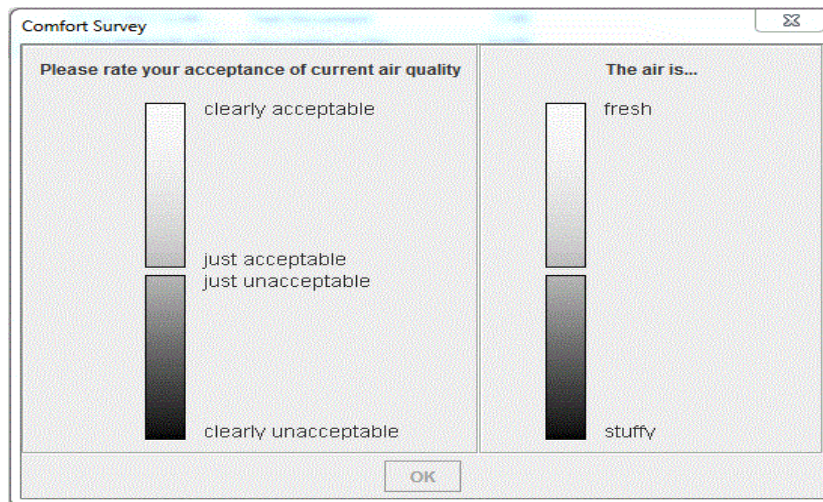


**Figure 2** Test schedule. Arrows indicate times when the survey are administrated

### 2.4 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. The questionnaire is composed by total thirteen questions. Every time that the survey was administrated it included all the thirteen questions. In Figure 2 arrows indicate times when the survey was administrated.

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



**Figure 3** Example of survey question



## 2.5 Subject training session carried out prior testing

All subjects attended one hour training session prior testing. The training session served the subjects to get familiar with the test procedure, and with the survey questions.

## 2.6 Measurements

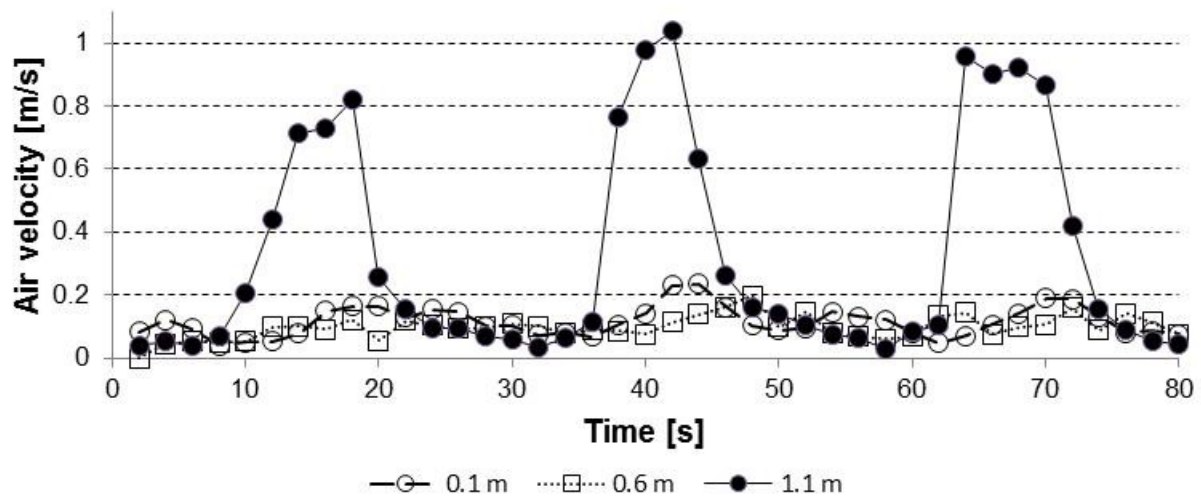
Room air temperature and humidity were measured at 1.1 m height.

Air velocity was measured for all the configurations in 27 points in the area where the subjects were supposed to be sat at 3 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). These three points has been selected as the most representative of the airflow experienced by the subjects for the six different configurations with the fixed fan. For the configurations with the oscillating fan, the maximum air velocities for the three points are comparable with value measured with the fixed fan, but there is a transitory phenomenon due to the fan oscillation. In Figure 4 it is reported an example of measured data for the configuration “3 Oscillating Front”. Velocity sensors at 0.6m and 0.1 m were shade from the air movement by the desk, so over time the air velocity was always low.

**Table 2** Measured air velocities and standard deviation

Configuratio n code	Mean value [m/s]/SD[m/s]		
	1.1 m	0. 6 m	0.1 m
2 Fixed Front	0.6	0.5	0.2
	8/0	1/	4/0
	.16	0. 11	.06
3 Fixed Front	0.8	0.6	0.2
	8/0	2/	8/0
	.13	0. 1 2	.07
2 Fixed Side	0.7	0.	0.3
	0/0	7	4/0
	.21	6/	.09

		0.8	0.	0.3
		1/0	7	5/0
3 Fixed Side		.29	9/	.19
			0.	
			4	
			8	
			0.	
			5	
2 Fixed	0.6		4/	0.2
Below	6/0		0.	4/0
	.20		2	.12
			5	
			0.	
			6	
3 Fixed	0.8		9/	0.3
Below	8/0		0.	1/0
	.49		2	.11
			7	



**Figure 4** Measured air velocity for configuration “3 Oscillating Front”

Air speed was measured with omnidirectional hotwire anemometers, with a response time of 2s and an accuracy of  $0.02\text{m/s} \pm 1.5\%$  of reading

### 3. Results

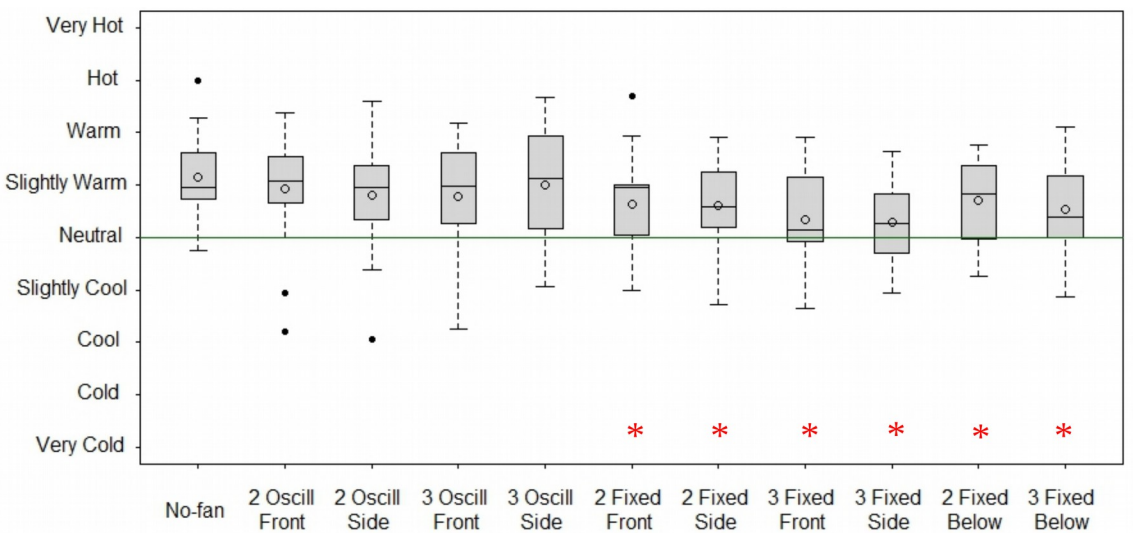
This paper focuses on stable conditions, analyzing subjects’ responses to the number seven and eleven surveys (see Figure 2), and leaving the results of the other surveys for future analysis.

### 3.1 Whole-body thermal sensation and thermal comfort

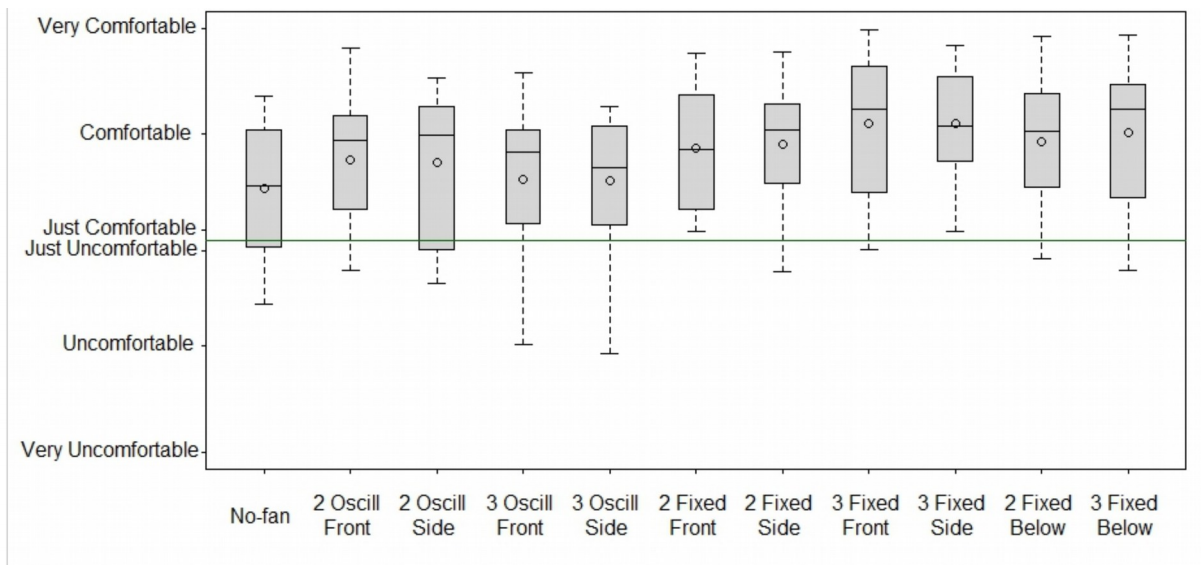
All the results for the configurations with fans were compared against the reference ‘no-fan’ condition. Statistical analysis was performed with a non-parametric method called a permutation test, using the program R [20]. In the graphs the symbol “\*” represents a statistically significant difference ( $p < 0.05$ ), and the dots represent outliers.

In Figure 5 the whole body thermal sensations are presented for the eleven configurations. It can be seen that there are no differences between “no-fan” and the “oscillating fan”-configurations. The differences are statistically significant between “no-fan” and all the six configurations with “fixed-fan”s.

Similar results were obtained for the whole body thermal comfort (Figure 6). From these two charts is clear that the amount of air movement generated with the oscillating fan was not enough to modify subjects’ thermal sensation, or to affect their thermal comfort.



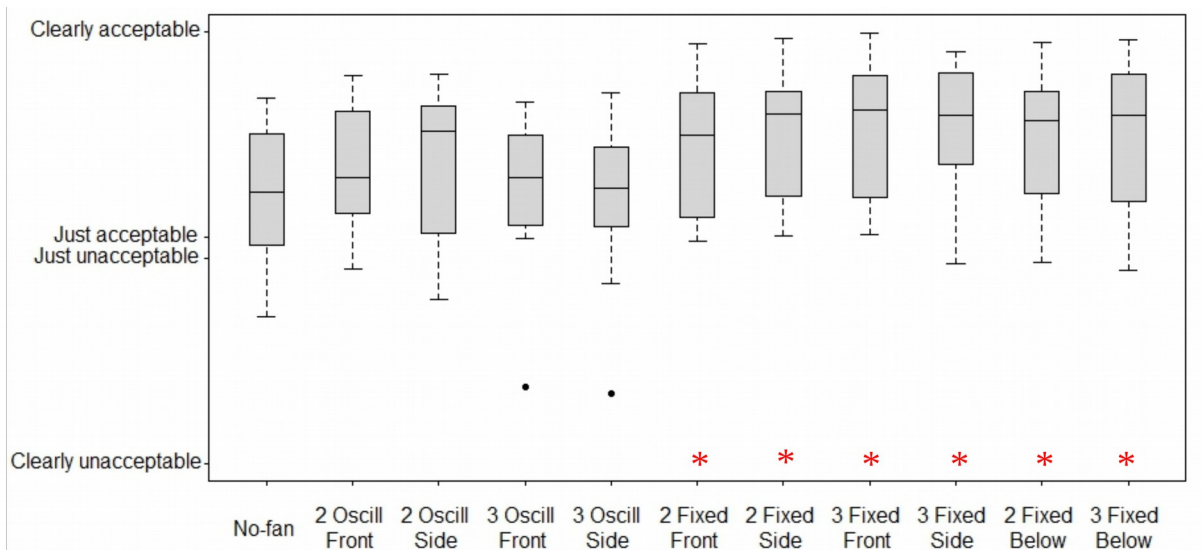
**Figure 5** Whole body thermal sensation



**Figure 6** Whole body thermal comfort

### 3.2 Thermal acceptability

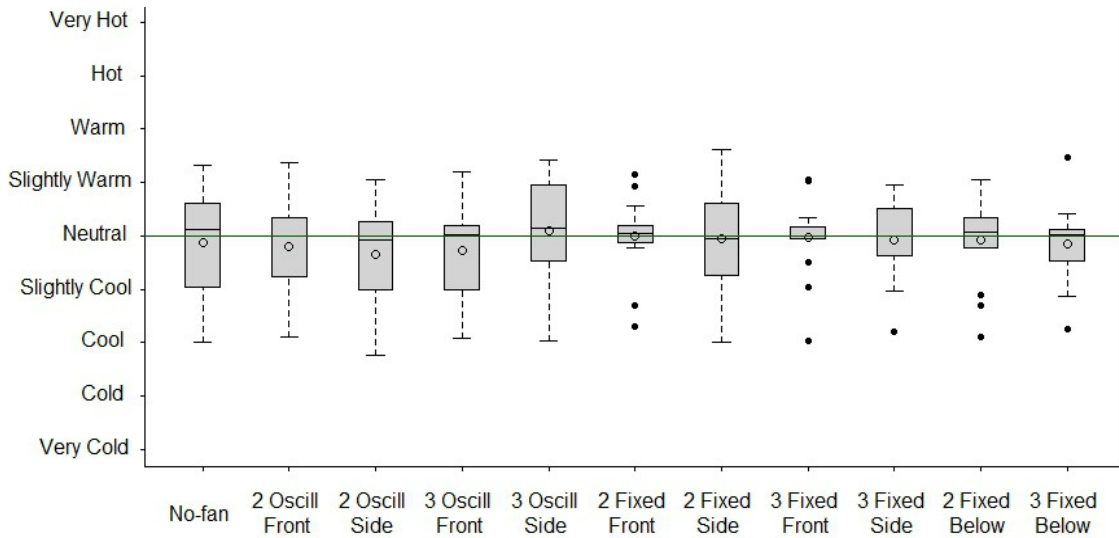
During the tests the subjects were asked to rate the acceptability of the thermal environment. The results are presented in Figure 7. Although some configurations of the oscillating fan showed an improvement over the no-fan reference case in terms of thermal acceptability, the result was not statistically significant. This may be related to the nature of the air movement generated by the oscillating fan, but also perhaps to the relatively small sample size. It is possible that the number of subject used for this work (16) was not enough to statistically show improvements caused by the oscillating fan.



**Figure 7** Thermal acceptability

### 3.3 Whole body preferred thermal sensation

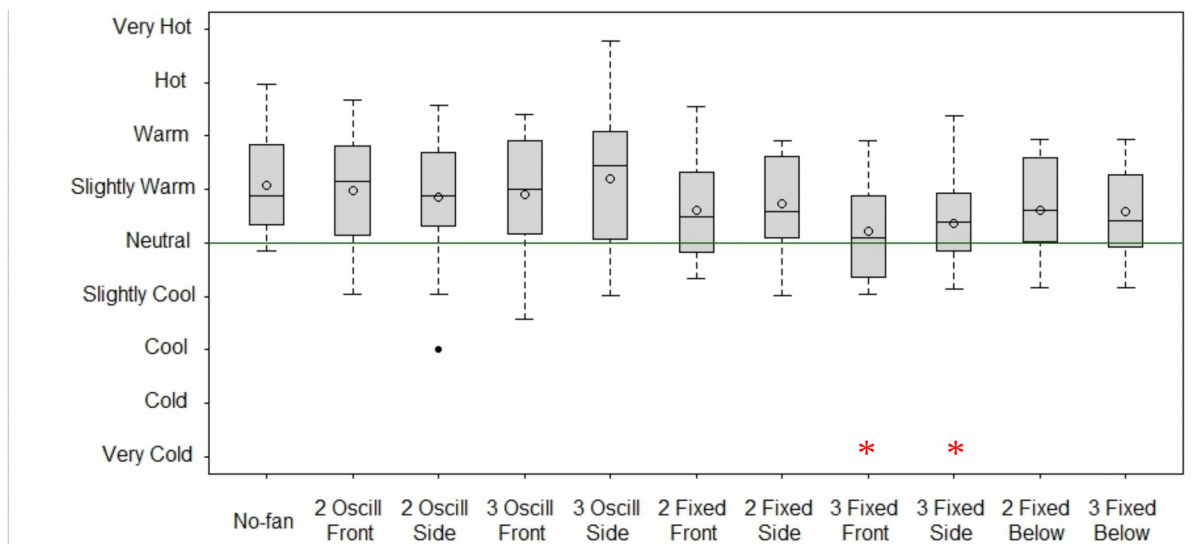
In line with a previous work [21] the preferred thermal sensation was not affected by the thermal sensation. Although there are some differences in terms of width of the distributions, the statistical analysis did not evidence any significant difference (see Figure 8).



**Figure 8** Whole body preferred thermal sensation

### 3.4 Face thermal sensation

The differences in face thermal sensation were statistically significant only for the configurations “3 Fixed Front” and “3 Fixed Side” (see Fig. 9). Differences for the other fixed-fan configurations had a p-value around 0.15. This result is not enough to say with confidence that there is a significant difference ( $p = 0.05$ ), but can be an indication that with a bigger sample size the difference would have been statistically significant.

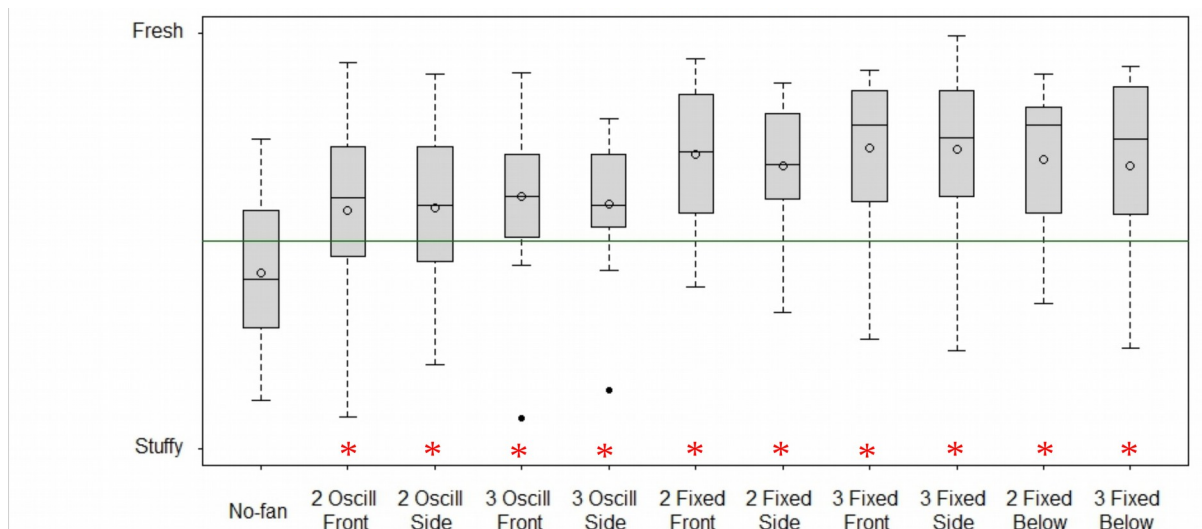


**Figure 9** Face thermal sensation

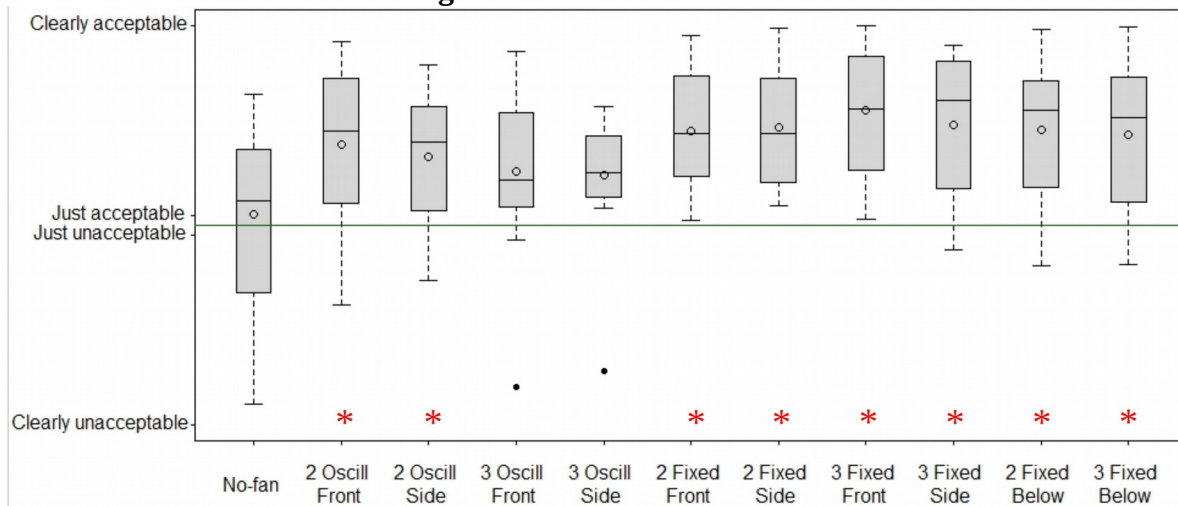
### 3.5 Perceived air freshness and air quality acceptability

Similarly to what Melikov and Kacmarczyk did [22] to investigate the perceived air quality, we used two questions in the survey: “Please rate your acceptance of current air quality” and “The air is...”, with a scale for this last that range from fresh to stuffy (see Figure 3). The acceptability scale was a continuous scale (see Figure 3) [23], which ranged from “clearly acceptable” (+1) to “clearly unacceptable” (-1), and was split in the middle with two labels “just acceptable” and “just unacceptable”.

In Figure 10 and Figure 11 the results for the “perceived air freshness” and “air quality acceptability” are reported respectively. The results for the two questions are very similar. Almost every configuration presents a statistically significant difference compared to the configuration “No-fan”.



**Figure 10** Perceived air freshness



**Figure 11** Air quality acceptability

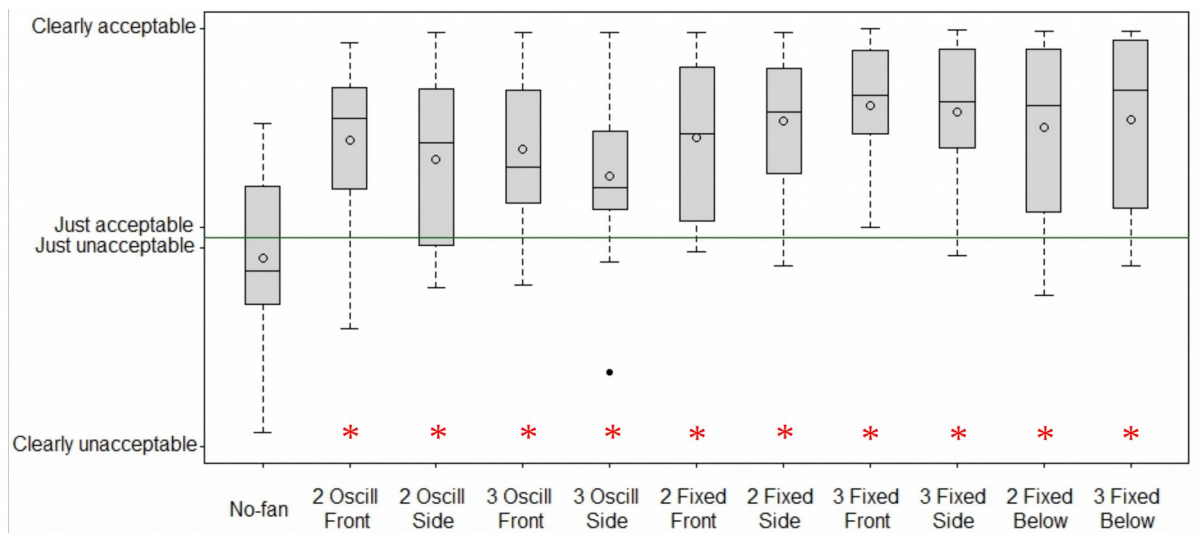
### 3.6 Air Movement acceptability and preference

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

As expected, for the configuration without fans, the majority of the subjects (94%) wanted more air movement. For the oscillating fan, more people wanted more air movement. For the fixed fan, more people wanted no change, and just few wanted less air movement. In Figure 12 the results for the air movement acceptability are reported.

**Table 3** Air movement preferences

Fan Configuration	Less air movement [%]	No change [%]	More air movement [%]
no-fan	0	6	94
2 Oscillating Front	0	56	44
2 Oscillating Side	0	44	56
3 Oscillating Front	0	44	56
3 Oscillating Side	0	38	63
2 Fixed Front	13	50	38
3 Fixed Front	0	75	25
2 Fixed Side	0	56	44
3 Fixed Side	19	56	25
2 Above	6	50	44
3 Above	13	56	31

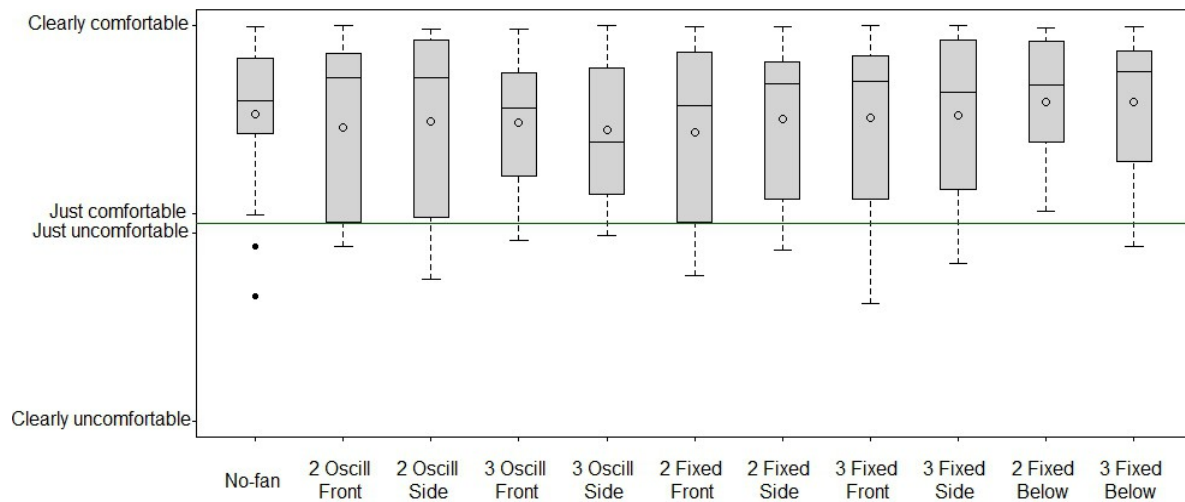


**Figure 12** Air movement acceptability

### 3.7 Dry-Eye Discomfort

Subjects were asked a question about dry-eye discomfort: “ Do you currently feel any discomfort due to dry eyes?”. The percentage of subjects who experienced dry-eye discomfort was minimal, ranging from 0% to 10%. The majority of the subjects who reported dry-eye discomfort placed their vote very close to the “just uncomfortable” line. The statistical analysis proved that there is no significant difference among the eleven configurations (see Figure 13).





**Figure 13** Dry-eyes discomfort

#### 4. Discussion

*Oscillating mode:* Compared to the no-fan reference configuration, neither the whole-body thermal sensation nor the whole-body thermal comfort was significantly affected by the oscillating fan. This negative result seems to be a result of the long oscillation period, especially the 15-second interval during which the airspeed at the occupant is effectively zero. This interval is long compared to the 10 seconds when the occupant received appreciable air movement. This type of intermittent air flow has not been addressed before. Previous studies of the comfort and sensation effects of fluctuating airflow were done by Fanger and Pedersen [24], Tanabe and Kimura [25], Arens et al. [26], and Hua et al. [27].

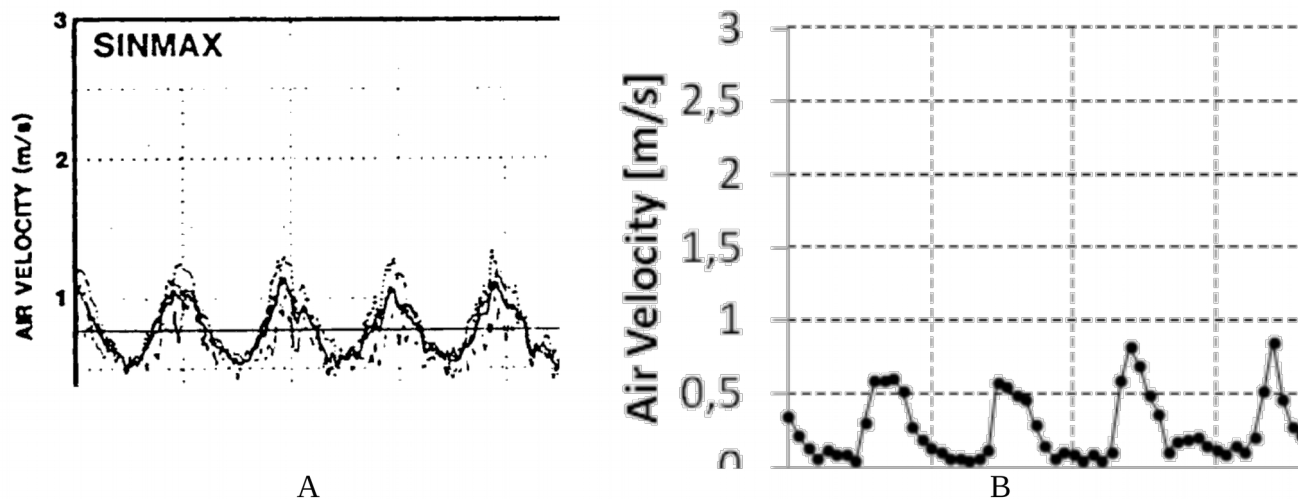
Fanger and Pedersen [24] studied draft discomfort under turbulence and found the maximum discomfort at 0.5 Hz. Tanabe and Kimura [25] tested different patterns of air movement, concluding that fluctuating air movement has a stronger effect on subjects' thermal sensation than constant air movement. As with Fanger, the authors reported an increased number of subjects feeling draft under fluctuating air movement (reaching peaks of 2 m/s) compared to those exposed to constant air.

The work of Arens et al. [26] points in to another direction. The authors concluded that the constant air speed provided more effective cooling compared to fluctuating air speed. The authors pointed out that the result was related to the specific fan used for the constant air movement. The constant speed mode of the

fan tested in Arens' work was not actually constant, producing a power spectrum peaking between 0.7 and 1 Hz, compared to 0.2-0.4Hz for the fluctuating mode. Previous work published by Ring et al. [28] shows that cold receptors in the skin have a peak sensitivity around 1 or 2 Hz, which matches the power spectrum peak of the 'constant' fan.

The study of Hua [27] studied a simulated natural wind (SNW) and a constant mechanical wind (CMW). on subjects' thermal comfort and thermal sensation, under two different environmental conditions, 28°C and 30°C. They found no statistically significant difference between thermal sensation vote of the SNW and CMW for either environmental condition, and a very small improvement in terms of thermal comfort vote only at 30°C.

The airflows used in these studies [25-27] fluctuated around an average air velocity and, unlike our study, the airflow never reached zero (see Figure 14). The subjects in the above-mentioned studies were always exposed to a certain minimum amount of air movement. This may explain the different conclusions of our work compared to the literature.



**Figure 14** Comparison between one of the air movement patterns studied by Tanabe and Kimura [25] (A), and one of the air movement pattern studied in this work (B).

*Fixed mode:* In contrast with the results for the oscillating fan, the configurations with the fixed fan showed an improved thermal comfort and a cooler whole body thermal sensation.

The remarkably low energy consumption of the new generation of DC fans emphasizes the role that these devices can play in saving energy in buildings. The results of this study show that a fan consuming 2-3 W can maintain comfort for an occupant in a warm indoor environment. Fans can improve resilience to future climate change in both existing and new buildings. They can be deployed to assist existing air conditioning (AC) systems or, in climates characterized by moderate temperatures, to help avoid the installation of new AC devices [29].

In terms of perceived air quality, almost all the fan configurations performed better than the still-air reference configuration. This result is in line with the literature [22,30,31]. However, the literature ascribes the improvements to whole-body thermal sensation, face thermal sensation, or cooling effect in the respiratory tract [32-34]. In the case of the oscillating fan in this study, there is a notable improvement in terms of air freshness and air quality acceptability, but no difference in thermal sensation compared to the base case. This suggests that a small amount of intermittent air movement, though insufficient to affect the subjects' thermal sensation, may improve their perception of the air quality. There can be two explanations to this phenomenon:

a) The amount of air movement is enough to disrupt the thermal plume that envelops the face. Plume disruption occurs at approximately 0.3m/s airspeed [22]. Disruption dilutes the bio-effluents and other pollutants picked up in nose and eyes, which the subjects may be able to perceive;

b) There may be some psychological sense of the outdoors and fresh air when feeling air movement. More research needs to be done to examine this effect.

A separate statistical analysis was done to verify whether there is any difference between front and side configurations. No statistical difference was found.

In terms of "air movement preference" the configuration "3 fixed 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.

The combinations of air velocities, air directions, temperature and humidity tested in this study did not cause any appreciable dry-eye discomfort. Fans blowing air from the ceiling at about 0.9 m/s toward the front, the side, or directly above the subjects' heads did not cause dry-eye discomfort.

## 5. Conclusions

- 1) The oscillating fan tested in this study had no statistically significant effect on subjects' thermal comfort or thermal sensation at 28°C. Further study should examine shorter recurrence intervals. There is a heightened perception of dynamic change in airspeed cooling, and at some shorter time interval this perception should outweigh the reduction of mean airspeed caused by a fan in oscillating mode.
- 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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