HUMAN PREFERENCE AND ACCEPTANCE OF INCREASED AIR VELOCITY TO OFFSET WARM SENSATION AT INCREASED ROOM TEMPERATURES

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ABSTRACT

Previous studies have demonstrated that in summertime increased air velocities can compensate for higher room temperatures to achieve comfortable conditions. In order to increase air movement, windows opening, ceiling or desk fans can be used at the expense of relatively low energy consumption.
The present climatic chamber study examined energy performance and achievable thermal comfort of traditional and bladeless desk fans. Different effects of mechanical and simulated-natural airflow patterns were also investigated. 32 Scandinavians, performing office activities and wearing light clothes , were exposed to a increased air movement generated by a personal desk fan. The subjects could continuously regulate the fans under three fixed environmental conditions (operative temperatures equal to 26 °C, 28 °C, or 30 °C, and same absolute humidity 12.2 Kg/m^3).
The experimental study showed that increased air velocity under personal control make the indoor environment acceptable at higher air temperatures. This will during summer season and in warmer countries improve thermal comfort without too high energy costs. There was significant individual difference in the preferred air velocities, which indicate that personal control is important. The accepted air velocities depended on the type and source of the increased velocity. The Scandinavian subjects did not accept so high velocities as found in studies with Chinese subjects.

KEYWORDS
Thermal comfort, air velocity, personal control, desk fan

INTRODUCTION

Buildings' construction and operation are considered of central importance on the path of a sustainable development. Passive techniques for heating and cooling have gained more and more audience for their feasibility, their efficacy and the positive effects on human health when compared to traditional air-conditioned systems. Previous studies have broadly demonstrated that in summertime increased air velocities can compensate for higher room temperatures to achieve comfortable conditions (from [1] to [4]). In order to increase air movement, windows opening, ceiling or desk fans can be used at the expense of relatively low energy consumption (from [5] to [7]).

METHOD

The present climatic chamber study examined energy performance and achievable thermal comfort of traditional and bladeless desk fans. Different effects of mechanical and simulated-natural airflow patterns were also investigated. 32 Scandinavians, performing office activities (1.2 met) and wearing light clothes (I_{cl} equal to 0.5-0.6 clo), were exposed to a direct air movement generated by a personal desk fan in continuous regulation under three fixed environmental conditions (operative temperatures (t_o) equal to 26 °C, 28 °C, or 30 °C, and relative humidity (*RH*) varying in the range of 40%-50% (at constant dew point of 14.8 °C)).

After an adaptation time, the subjects were invited to adjust the air movement for achieving their preferred thermal comfort. Is the preferred equal to the predicted thermal comfort? Will the personal control or different type of fans affect the results?
The individual preferred air velocities were recorded, and the relative energy consumptions were collected in order to estimate the potential energy savings when comparing to AC systems.

Experimental SET UP

The experiment was carried out in an office-like climatic chamber with dimensions 5.9*5.8*3.2 m^3 at the International Centre for Indoor Environment and Energy of Technical University of Denmark (ICIEE-DTU). The chamber reproduces a typical office room, providing occupants with a view on the outdoors garden. Internal and external blinds can be operated in order to let diffuse sunlight enter the room and meanwhile shade the direct sunlight. Eight workplaces, 4 on the right side and 4 on the left, were arranged with desk, office chair, desk lamp, and desk fan. A partition between the right and left side was located in the middle of the room in order to avoid any possible influence of air moviment due to others occupants (see Figure 1).

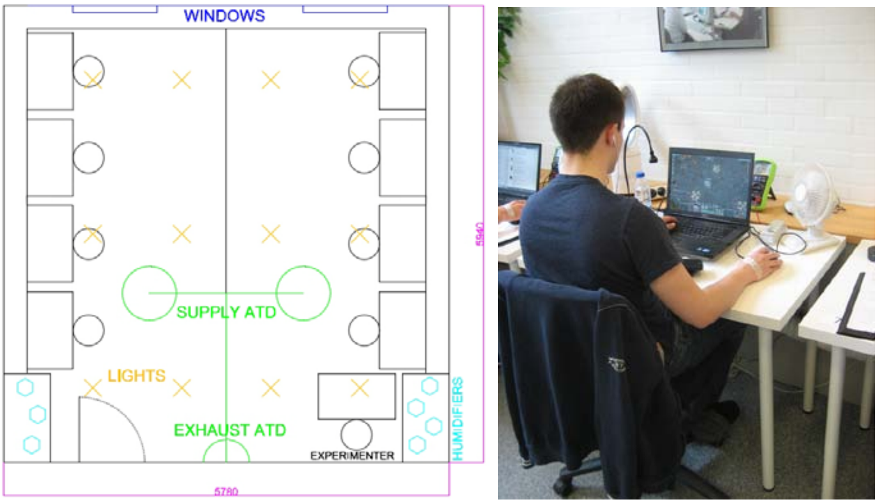

Figure 1. a) Sketch of the experimental chamber, b) view of workplace set up

The air and globe temperature sensors, developed at the ICIEE-DTU [8], have been calibrated for a temperature range of 20-35 °C with an accuracy of ±0.3°C and used during the experimental measurements. Omnidirectional anemometers were used for mesuring air velocity. Temperatures and air velocity at 0.1, 0.6, 1.1 m and 1.7 m heigh above the floor level were recorded in the center of the room.The skin temperatures of both hands and forehead of the subjects were continuously recorded. For the skin temperatures measures iButtons sensors were used as suggested by van Marken Lichtenbelt et al. [9] and Smith et al. [10]. During the experiment three different types of desk fans were used:

- 8 common two-steps desk fans which were regulated with a dimmer switch in order to obtain a continuous variation of the air speed (**CF** = Continuous regulation Fans)
- 2 bladeless fans (**BL**)
- 2 fans which simulate natural wind (**SN)**

The voltage applied to the CF fan has been correlated with the air speed generated at a distance of 60-70 cm from the fan, distance that intercor between the occupant and the fan, so that the air speed profile for each exposed participant was recovered by the recorded voltage data. The SN fans used on the present experiment were built at Tsinghua University, Beijing, China, where they have been used in a previous experiment with Chinese subjects [11].

Along the experiment the subjects were asked to fill in twelve surveys, 4 *long* and 8 *short* (containing respectively 19 and 10 questions) regarding: 1) thermal environment, namely thermal comfort, thermal acceptability, thermal preference, air movement preference, local thermal sensation and air movement sensation; 2) air quality, namely acceptability of air quality, perception of air humidity, preference on air humidity; 3) satisfaction with light and noise level; 4) experience of symptoms such as headache, dry eyes, irritated throat and nose irritation.
A total of 32 Scandinavian voluntiers with good health participated in the experiments, most of them being university students. Their anthropometric data are reported in Table 1.

Sex	**No. of subjects**	**Age (years)**	**Height (cm)**	**Weight (kg)**	**Du Bois area (m^2)**	**Body Mass Index (BMI)**
females	16	23 ± 2	170 ± 6	66 ± 10	1.76 ± 0.14	22.9 ± 3.6
males	16	25 ± 4	180 ± 9	78 ± 22	1.97 ± 0.26	23.8 ± 5.0
females + males	32	24 ± 4	175 ± 9	72 ± 18	1.86 ± 0.23	23.3 ± 4.3

Table 1. Anthropometric data of the subjects.

Each subject was esposed at three different conditions of 4-hours experiments in different days. The subjects were asked to wear a typical summer clothing ensemble, consisting in: panties/briefs, bra (if female), T-shirt, jeans or normal trousers, light socks, trainers or normal shoes. No garments that would protect the subjects from the air movement were allowed. The overall clothing insulation, considering the chair insulation of 0.1 clo (EN ISO 7730), resulted of about 0.5-0.6 clo.

Experimental procedure

The conditions investigated in the experiment are reported in Table 2.

Condition	**t_o [°C]**	**RH %**
A	26	50
B	28	45
C	30	40

Table 2. Physical parameters set during the experiment.

The relative humidity was set in order to keep the dew point constant at 14.8 °C. All experiments were carried out in afternoon sessions, in order to exclude confounding factors related to the circadian rhythms of the participants. Eight participants were esposed at the same time and at the same condition. They were allowed to work at their laptop, read a book or perform similar sedentary activities estimated equal to 1.2 met. The exposure time of each condition last in total 4 hours and only comsumption of provided mineral water was allowed. Each condition consisted in 4 periods, as reported in table 2, with the adaptation time followed by three rounds of exposure to different air velocities or type of fans.
During the adaptation time (AD) the occupants were exposed for 90 minutes at the room environment having 0.5 m/s of air movement at the upper body part generated by the CF desk fan; it was extlabished during the pre-test analyses. The three round text consisted on 30 minutes of exposure where the occupants were encouraged to freely adjust the air speed level of their desk fan (with fixed orientation) and 15 minutes of exposure to their preferred air velocity. At the end of each round the subjects were assigned to another desk and different type of fan. Each round consisted of same principle and exposure time.
CF fan was connected to a multimeter, which allowed to record the voltages correspondent to the preferred air velocities. The experiment was conceived to that in each session four

subjects would be exposed to all three different types of fans, whereas the other four subjects would experience twice the exposure to the CF fan.

	Adaptation	1st round		2nd round		3rd round	
air movement	0.5 m/s	free adjust.	fixed setting	free adjust.	fixed setting	free adjust.	fixed setting
abbreviation	**AD**	**1 R**	**1 R***	**2 R**	**2 R***	**3 R**	**3R***
duration [min]	90´	30´	15´	30´	15´	30´	15´

Table 3. Time schedule of the experimental condition.

RESULTS

Table 4 reports the usage of fans at the different environmental conditions (data from R1*, R2* and R3* are pooled). The three types of fans presented peculiar differences of usage. In condition A the CF fans were used by 71% of subjects, whereas only 26% and 35% used the BL and the SN fans, respectively. In condition C a vast majority of subjects kept the CF on. The usage of BL fans increases by 32% and 33% from condition A to B and from B to C, reaching 91% of usage in condition C. While the SN fans had a large increase of use from condition A to B (65%) and slightly decrease from B to C (4%).

% USAGE of FAN	CF		BL		SN	
condition	**% on (n)**	**% off (n)**	**% on (n)**	**% off (n)**	**% on (n)**	**% off (n)**
A	71 (22)	29 (9)	26 (6)	74 (17)	35 (8)	65 (15)
B	89 (29)	11 (3)	58 (14)	42 (10)	100 (18)	0 (0)
C	97 (30)	3 (1)	91 (21)	9 (2)	96 (22)	4 (1)
(n) represent the number of exposed participants						

Table 4. Usage of fans at the different environmental conditions

Resulted analyses when CF fans were used

The mean preferred air velocity (±standard deviation (SD)) of the three investigated conditions when CF fan was used are reported in Figure 2. It is increasing from condition A to B to C (from 0.56 m/s to 0.69 m/s to 0.85 m/s).
No statistically significant difference was found between male and female subjects.
The number of subjects choosing a certain air velocity is reported in Figure 3. In condition A nine subjects chose to keep the fan off, and 17 subjects chose an air speed between 0.3 and 0.7 m/s. In condition B the highest preferred air velocity was 0.5-0.6 m/s,while 0.9 m/s was chosen in condition C. A tendency towards higher air speeds at increasing air temperatures is clearly visible, large individual can still be observed.

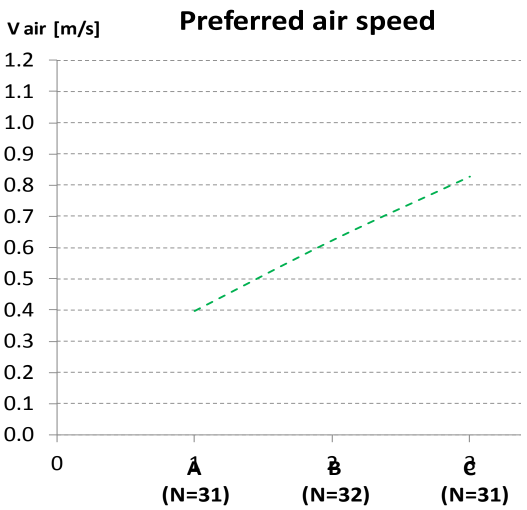

Figure 2. Preferred air velocity at the three investigated conditions.

The mean skin temperature (± (SD)) are reported in table 5 for the occupants exposed to the use of CF fan and for subjects not using their desk fan. The difference was found to be significant in condition A ($p < 0.0001$) and condition B ($p < 0.002$) for the forehead skin temperature, confirming the cooling effect of the CF fans. A slight decrease of forehead skin temperature was noticed with the increasing air velocities. No significant difference was observed between male and female.

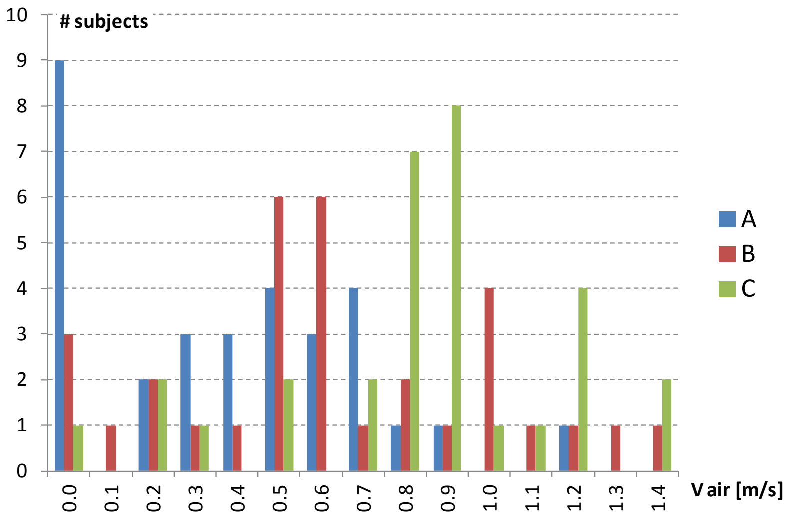

Figure 3. Number of subjects choosing a certain air velocity.

TEMPERATURE ±SD	Forehead (°C)		Right hand (°C)		Left hand (°C)	
Condition	CF-ON	Fan-OFF	CF-ON	Fan-OFF	CF-ON	Fan-OFF
A	33.0±0.4	34.2±0.8	31.6±1.0	32.4±1.1	31.6±1.0	32.4±1.0
B	33.8±0.6	34.5±0.5	33.1±0.8	33.5±0.7	33.3±0.9	33.2±0.7
C	34.2±0.6	34.8±0.7	33.9±0.7	34.0±0.8	34.1±0.6	34.0±0.8

Table 5. Mean skin temperature of forehead, right and left hands of subjects using the CF fans and not using local air moviment.

Responses on the thermal environment

Table 6 shows the mean thermal sensation votes (TSV) for females and males at the three investigated conditions. Females felt slightly warmer than males in condition C, but the difference was not statistically significant. The mean TSV increased with increasing room temperatures, passing from neutrality (0) in condition A to “slightly warm” (+1) in condition C. A comparison of mean TSV between subjects using the CF fan and not using any local air movement is shown on the right side in Table 6. In conditions B and C a slight difference can be noticed, as expected the occupants using the fans tend to have a slightly cooler thermal sensation; butthat is not statistically significant.
The thermal environment for subjects using CF fans was generally considered acceptable in conditions A and B, while it became critical in condition C, with a percentage of dissatisfied rising up to 55%.

TSV ±SD				
condition	**females**	**males**	**Fan On**	**Fan Off**
A	0.0±0.6	-0.1±0.7	0.0±0.6	0.0±0.6
B	0.5±0.6	0.7±0.9	0.5±0.7	0.8±1.0
C	1.5±0.6	1.1±0.7	1.3±0.7	1.7±1.1

Table 6. TSV organized by sex and by the use or not of the CF fan

Figure 4a reports the actual TSV and the Predicted Mean Votes (PMV) of subjects using the CF fans. As shown in figure 4b, the PMV model confirmed to be a fairly good predictive tool for Danish people. In the warm side the percentage of dissatisfied rapidly increases from “neutral (0) to “slightly warm” (+1) to “warm” (+2) as for the PMV/PPD model; while a large discrepancy was found in the “slightly cold” (-1) condition where 26% of people dissatisfied were expected.

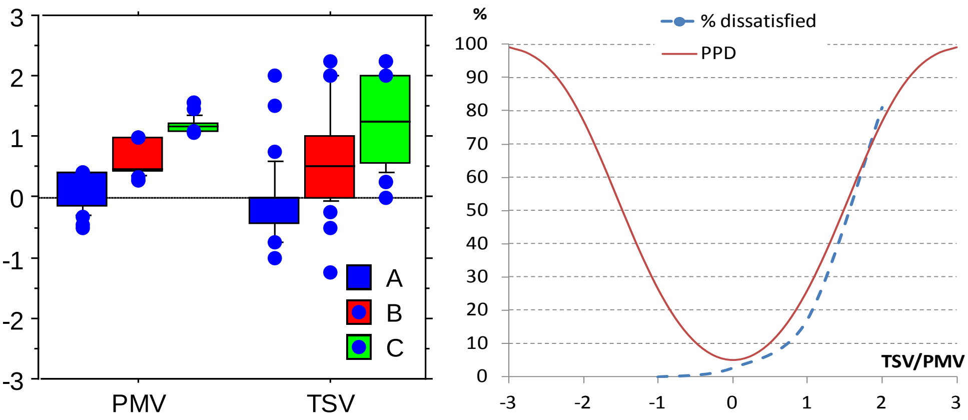

Figure 4. a) Comparison of PMV and TSV; b) Comparison of PMV/PPD model with present results.

The thermal preferences at the three conditions are reported in Table 7. Despite the subjects could increase the air movement, they were not able to reach a satisfying thermal comfort. Infact, in condition C about 85% of the subjects operating CF fans were asking for a cooler environment.

	Thermal preference		
condition	**warmer**	**no change**	**cooler**
A	4	13	5
B	0	12	16
C	0	4	25

Table 7. Thermal preference at the three investigated conditions.

No correlation was found between TSV and preferred air velocity or TSV and forehead skin temperature.

Responses on air movement

The vast majority of the subjects using their desk fan could feel air movement. The body parts where the air movement was most commonly felt were the face (more than 95%) and the right arm (60% to 85% depending on the fan type). It was noted that 20 % of subjects keeping their fan off could anyway feel air movement. The mostly recurrent body part where the air movement was felt was the right arm, possibly due to the chosen setting (fan on the right side of the desk, thus blowing partly towards the right arm of the desk neighbour, see Figure 1b.
In Table 8 are reported the acceptancy of the use of different type of fan for the three investigated indoor thermel conditions. Reminding the limits conditions of the draught (DR) model (reported in ISO7730), DR were calculated at different air velocities for an environment having 26°C and 30% of turbolence (Tu) and reported in Table 9.

	CF		**BL**		**SN**		**OFF**	
	acc.	not acc.	acc.	not acc.	acc.	not acc.	acc.	not acc.
A	21	1 (5%)	2	4 (67%)	6	2 (25%)	43	3 (7%)
B	27	2 (7%)	10	4 (29%)	14	4 (22%)	10	6 (38%)
C	22	8 (27%)	11	10 (48%)	15	7 (32%)	2	2 (50%)

Table 8. Air movement acceptability for the different types of exposure.

DR %	5	9	13	17	22	27	32	37	42
V air [m/s]	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5

Table 9. Draught risk at 26 °C and 30% Tu for increasing air velocities

DISCUSSIONS

Preferred air velocity

When analysing the preferred air velocity (v_{air}), a preliminary question pops up: "Preferred by who?". In order to give a complete view of the human behaviour and response in the present experiment, at least three different groups of subjects can be analysed.

The first group is constituted by all subjects sitting at a desk equipped with a CF fan. This group can be seen as the most representative, however about 30% of the subjects kept their CF fans off in condition A, resulting in low values of mean air velocity of the whole group.

A second group can be identified in the subjects actually using the CF fans. In this way the mean air velocity will not be affected by the null data of the subjects keeping their fan off. In this case, it is important to keep in mind what was the actual usage of the CF fans during the three conditions.

A third group can finally be constituted by those "comfortable subjects" expressing acceptability for both the thermal environment and the air movement, and voting between "slightly cold" (-1) and "slightly warm" (+1) in TSV scale. This group is not reflecting the actual mean level of satisfaction of the experimental sample, but it can be useful to point out which environmental parameters may potentially result in an acceptable thermal balance. It should be noticed that in condition C only 11 subjects (35%) are considered "comfortable".

The TSV and the preferred air velocity of the three mentioned groups is reported in Table 10, where also the effective number of subjects in the three conditions is indicated.

Condition / Group	**A**		**B**		**C**		**Nr. of subjects**		
	TSV±SD	v_{air} ±SD	TSV±SD	v_{air} ±SD	TSV±SD	v_{air} ±SD	A	B	C
	[-]	[m/s]	[-]	[m/s]	[-]	[m/s]	[-]	[-]	[-]
CF on&off	0.0 ±0.6	0.40 ±0.32	0.6 ±0.8	0.62 ±0.36	1.3 ±0.7	0.83 ±0.34	31	32	31
CF on	0.0 ±0.6	0.56 ±0.23	0.5 ±0.7	0.69 ±0.31	1.3 ±0.7	0.85 ±0.30	22	29	30
comfortable	-0.2 ±0.4	0.41 ±0.29	0.4 ±0.5	0.64 ±0.33	0.6 ±0.3	0.91 ±0.25	26	22	11

Table 10. TSV and preferred air velocity in the three investigated conditions.

PMV and TSV

The PMV resulted to be a good indicator of TSV. The PMV index was actually devised on the basis of tests conducted mainly on subjects from temperate climates. Studies conducted in tropical climates ([13], [14], and [15]) show that the PMV overestimates the thermal sensation of people, and it is today recognized that it is necessary to take into account the adaptation of people to their local climate.

A study by Humphreys & Hancock [16] questioned "what is the actual preferred thermal sensation of subjects expressing their TSV on an ASHRAE scale?". They found that the most common personal desire was "neutral" followed by "slightly warm" and that it varied with the TSV currently experienced. The data were collected in dwellings and lecture rooms for temperatures between 16°C and 24 °C. In the present work the same question resulted in "neutral" tending to "slightly cool" desire for condition A and B, and "slightly cool" in condition C. The different result suggests that culture and climate may affect people's thermal preferences.

On SN fans use

The SN fans provided an average air velocity of 0.7 ÷ 0.8 m/s, with a dynamic profile of air velocities and gusted up to 1.4 m/s. The comparison between TSV of the present study with the previous one performed by Hua (et al. [11]) is shown inFigure 5. In the Chinese experiment the subjects felt on average cooler than the Danish ones, with a difference in TSV of 0.6-0.7 units on the ASHRAE TSV scale at 28°C and 30 °C.

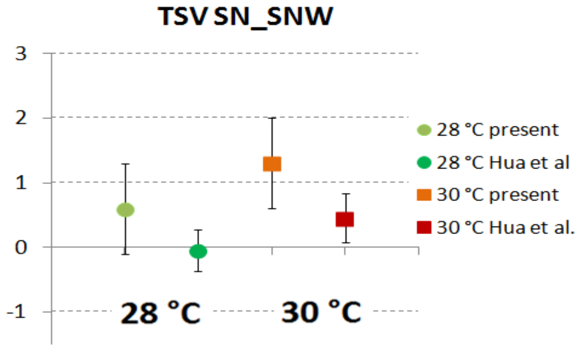

Figure 5. Comparison between TSV of the present study and Hua`s similar experiment.

Sixty percent of the subjects using the SN fans were asking for less air movement in condition A, while 40% of them requested more air movement in condition C. This may imply that the dynamic airflow profile should be adjusted to the room temperature in order to guarantee a proper cooling effect.

On BL fans use

BL fans could not be operated at low air velocities (lower than 1.3 m/s), it implied that a consistent number of subjects were asking for less air movement and when possible preferred to turn it off. The BL fans had a strong cooling effect in condition A (see figure 6), causing a mean drop in the forehead skin temperature of about 1.4 °C more than the one obtained by the use of CF fans that was 2.6 °C lower than when no local air movement was used. The difference is less evident in the room conditions where temperatures are higher

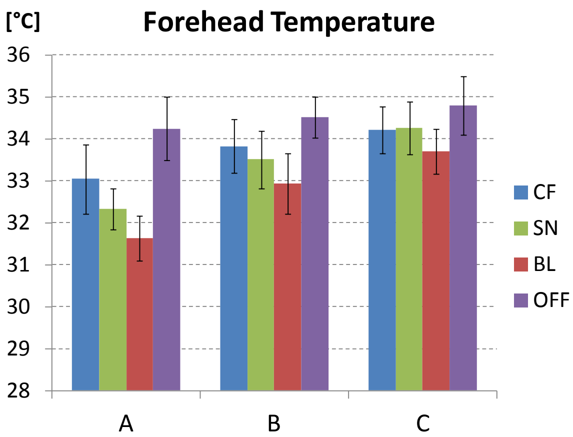

Figure 6. Forehead mean skin temperatures at different room conditions and fans exposure

The bladeless fans present an attractive design style, and the different airflow pattern (a rather constant, non-buffeting airflow) that could result in a high level of comfort. However, new prototypes with also a wider range of air velocities, starting from 0.2 m/scirca, is suggested.

Impact of the operability of CF, BL, and SN fans

The characteristics of the desk fans imposed several limits of use:

- The CF fans had an upper air velocity setting of 1.2-1.4 m/s. It implied that the subject could not further increase the air velocity. However, none of the subjects choosing the highest air velocity asked for more air movement.
- The experimenter was setting the simulated-natural mode of the SN fans. It appeared having an influence on the behaviour of the occupant that repeatedly asked for changes of the fan setting.
- The operability of BL fans operating only at high range of air velocities, reduced the flexibility of use in a sort of on/off use.
- A minor role could have been played by the **aesthetics** of the three types of desk fans, both caused by their “design pleasantness” and by the “perceived familiarity”.
- Noise appeared to be one of the reasons why the occupants preferred not to increase the air velocity of the provided fans having instead a warmer thermal sensation. That was mainly related to the BL fan use that increased from 45 dBA to 54 dBA in the middle of the room when it was switched on and it could reach 72 dBA at the occupant place.

Several subjects indicated that their preferred air velocity was chosen as a trade off between the cooling effect and the drying effect on the eyes.
The present study confirmed the findings of Fang et al.[12], who observed that the perceived air quality (PIAQ) decreases with increasing air temperature and humidity. The use of desk fans has to be carefully considered also as regards the eventuality of cross infection.

CONCLUSIONS

The experimental measurements showed that higher air velocity and personal control make the indoor environment acceptable at higher air velocity with a benefit on energy consumption applicable during the summer seasons and in warmer countries. There was significant individual difference in the preferred air velocities, which indicate that personal control is important. The accepted air velocities depended on the type and source of the increased velocity.
The PMV resulted to be a good indicator of TSV, however the PPD curve overestimated the percent of people dissatisfied. The “slightly cool” sensation was actually chosen by 45% of subjects as preferred TSV in condition C, suggesting that culture and climate may affect people’s thermal preferences.
The responses from subjects exposed to a simulated natural airflow suggest that the dynamic airflow profile should be adjusted to the room temperature in order to guarantee a proper cooling effect.
Although the bladeless fans had a consistent cooling effect, their low flexibility of use resulted in a large number of subjects dissatisfied. New prototypes with a wider range of air speeds should be designed for a deeper investigation on the potentialities of this technology.
The fan usage did not show correlation with perceived indoor air quality, while it was observed that with the increasing of air temperatures the indoor air quality was negatively perceived.

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