Impact of a task-ambient ventilation system on perceived air quality

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Perceived air quality, Air movement, Airspeed, Ventilation, Task-ambient conditioning

SUMMARY
Air movement can provide comfort in warm environments in energy-efficient and cost-effective ways. However, there have been suggestions that people's perception of air quality reduces with increased air temperature, which could preclude the air-movement approach to comfort control. We examined this issue in a human subject test in neutral (24.5ºC) to warm (28ºC, 30ºC) temperatures, with a range of air speeds provided from two sides into the face and breathing zone. Perceived air quality (PAQ) was significantly improved by airspeed. At 28ºC, re-circulated room air at 1 m/s airspeed produced PAQ equivalent to that found under the neutral condition. Mechanisms of how air movement affects PAQ are discussed. In warm environments, air movement can provide high levels of both thermal comfort and perceived air quality.

INTRODUCTION
A body's overall discomfort has been shown to be dictated, in warm conditions, by warm head and hands, and in cool conditions, by cool feet and hands (Arens et al. 2006, Zhang 2003). We used this finding to design a task-ambient conditioning (TAC) system that heats only the feet and hands, and cools only the hands and face, to efficiently provide comfort in a wide range of ambient environments. The cooling is largely done through convective cooling by air jets directed on or near the skin.

In buildings, it is energy-efficient to offset high indoor air temperature setpoints with air movement that cools the body. However, there have been studies in which occupants' perceived air quality (PAQ) decreased as air temperature increased (Fang 1994, 1998). If PAQ were related to air temperature (as opposed to, say, the body's thermal balance) air movement cooling would become unacceptable as a mode of environmental control. There is some contrary evidence (Zhang et al. 2007): a well-instrumented field study of a naturally ventilated office building found better PAQ in summer than in winter, although the average summer air temperature was 1.4ºC higher. That study had not been designed to focus on the relationship between PAQ and airspeed, and it did not provide data specifically linking the two variables. It suggested that we needed a better understanding of how airspeed influences people's perceived air quality. We examined this in a human subject test of the TAC system.

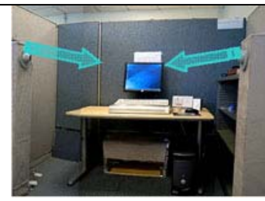
METHODS

The TAC system consists of 4 subcomponents (palm warmer, foot warmer, face ventilation device, hand ventilation device, Figure 1) to heat hands and feet in cool environments, and to cool face and hands in warm environments. The face ventilation TAC device provides air from the sides into the breathing zone, in order to avoid dry-eye discomfort from air directed into the eyes (Wyon and Wyon 1987, Wolkoff et al. 2005), and also draft sensations from air impinging on the back of the neck (Fanger et al. 1988).

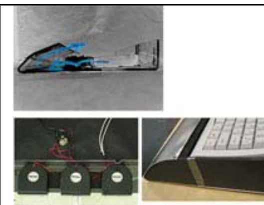
Cold conditions

Foot warmer

Warm conditions



Face ventilation

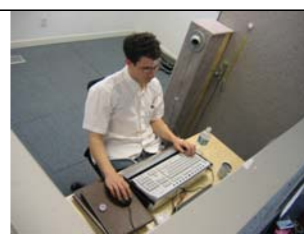


Hand cooling device

Figure 1. Four components of the TAC system

We tested 5 ambient air temperatures, two cooler ones representing winter conditions (18 ºC and 20ºC), two representing summer conditions (28 ºC and 30ºC), and a neutral condition for each season (Table 1). Eighteen subjects (9 male and 9 female) participated in each of the 5 test conditions, for a total of 90 three-hour tests. Each test was divided into 3 one-hour sessions, corresponding to three control strategies: No-TAC, Fixed-TAC, and User-Controlled TAC. The sequence of the three sessions was alternated to keep a balanced order. Figure 2 shows the chamber setup. Because we provided different clothing for winter and summer conditions, there are two neutral condition temperatures, 24.5ºC and 25ºC, respectively.

Subjects with 0.66 clo winter clothing



Subject with 0.5 clo summer clothing

Figure 2. Chamber setup and clothing

Table 1. Chamber air temperatures and effective temperatures

Condition	Room air temperature	Effective temperature (ET*)
hot	30ºC (86ºF)	29.0 ±0.1ºC
warm	28ºC (82.4ºF)	27.5 ±0.1ºC
neutral	25 or 24.5ºC (77ºF or 76ºF)	24.2 ±0.1ºC
cool	20ºC (68ºF)	19.9 ±0.1ºC
cold	18ºC (64.4ºF)	18.0 ±0.1ºC

In the 28ºC 'summer' condition test, air motion was provided through the head and the hand ventilation devices, both using re-circulated room air. The 30ºC tests were the same as the 28ºC tests, except that the head cooling airflow in this case was outside air, supplied at 24ºC (6ºC cooler than the room air temperature). Due to mixing, the air reached the breathing zone of an occupant around 28ºC. Note that under neutral conditions, there is no 'Fixed TAC' condition, because at neutral we assumed that the occupants would not need any local conditioning.

We measured subjects' skin and core temperatures, and surveyed their subjective responses regarding to thermal comfort, perceived air quality, air movement preference. The subjective survey was administered at 30 minutes intervals, with a survey at the beginning of each test session, one in the middle, and one at the end. The questionnaires are shown in Figure 3.

The PAQ survey uses a continuous scale running from 'just acceptable' (+0) to 'very good' (4), 'just unacceptable' (-0) to 'very bad' (-4). There is a gap between 'just acceptable' and 'just unacceptable' to force the subjects to make a clear distinction between acceptable and unacceptable. Similar scales were used for air movement acceptability and eye comfort. Air movement preference was presented as three choices.

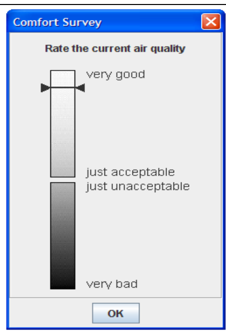
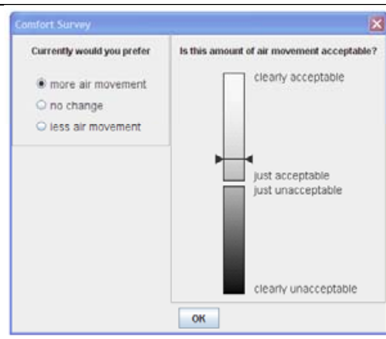
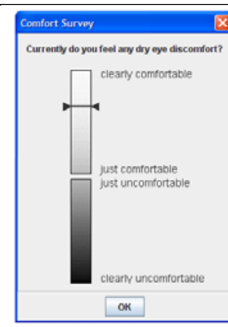
		
Perceived air quality	Air movement preference and acceptability	Dry-eye discomfort

Figure 3. Perceived air quality and air movement related questionnaires

RESULTS

The TAC system maintains occupant comfort over the tested temperature range 18 – 30ºC. In this paper, we focus on the influence of airspeed on perceived air quality. See Zhang et al. (2008) and Kim et al. (2008) for the detailed description of the TAC system design, subjective survey questionnaires, comfort results and energy analysis.

Perceived air quality and air movement.

The lower red curve in Figure 4 presents the perceived air quality (PAQ) under 30ºC air temperature, under fixed velocities without User Control. It shows that PAQ is significantly better with 1 m/s air movement at the breathing zone than with still air (increased by 2.4 scale units, from –0.8 to 1.6; $p<0.001$).[1]

[1] (The small 'n' number for the air speed 0.5 m/s results from a small number of tests we did at that condition early in the project when the overall test duration was four hours. We found that four hours was too long for the subjects, and that their performance was lowered toward the end of each test. In order to drop this last hour, we chose to drop the 0.5 m/s condition

Since in the 30ºC tests the nozzle air supply was cooled (24ºC at the outlet of the nozzle, about 28ºC when it reaches the breathing zone), and coming from the outdoors, one might attribute the improved PAQ to three causes: air movement, lower air temperature, and/or the freshness of the supply air.

The middle curve in Figure 4 tends to reject both lower supply air temperature and fresher supply air as causes of the improvement. This curve represents the 28ºC room condition (also fixed velocities without User Control), in which the nozzle supply air was entirely re-circulated room air drawn from near the floor. Since the air temperature and freshness were identical to those of the surrounding room air, the 1.6 scale unit improvement in PAQ at 28ºC ($p<0.001$) must be attributed to air movement. This is further supported by the top curve in the figure representing neutral temperature, with the airspeed under User Control. In this, the PAQ under neutral conditions was increased (0.6 scale, $P<0.004$) when subjects increased the air speed. Again, the moving air was re-circulated room air. No cooled or fresh supply air was involved.

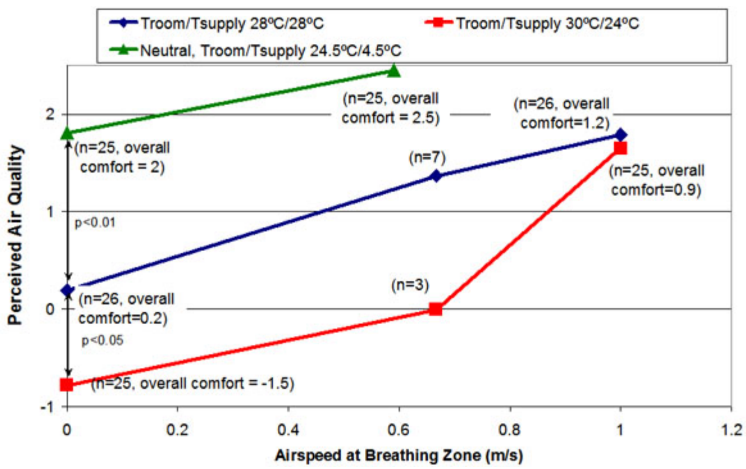


Figure 4. Perceived air quality versus air speed measured in the breathing zone

The large difference in PAQ seen between the air temperatures 28ºC and 30ºC under still air (middle and bottom curves, $p<0.05$) dropped to a small difference when the air speed was 1 m/s. Air movement caused part of this improvement. Presumably the cooler supply air provided in the 30ºC ambient tests (which reached the breathing zone at 28ºC) also improved PAQ.

Figure 5 shows the increases in PAQ for a range of airspeeds that were chosen by the user (User-Control), relative to still air (No-TAC). Each line represents the results measured for 18 subjects. The velocities were chosen by the subjects. It shows that when the air temperature was high (28 and 30ºC in the figure), the higher the airspeed, the better the PAQ. Under neutral conditions, once the air velocity reached about 0.3 m/s, further airspeed did not enhance the PAQ.

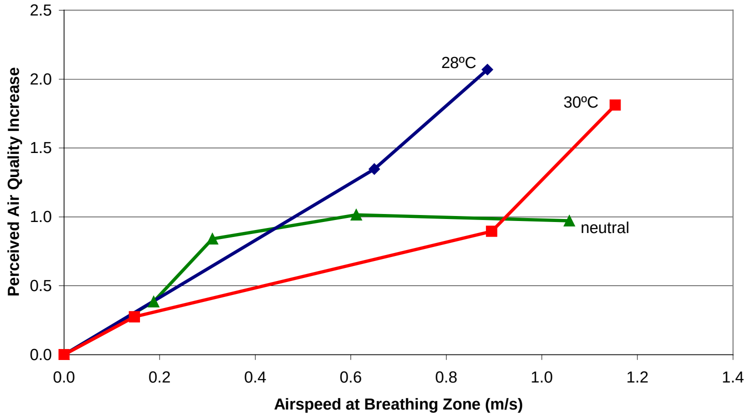


Figure 5. Increases in perceived air quality caused by air speed, at three temperatures (user-controlled TAC)

Figure 6 allows us to further examine how much air movement improved PAQ. Under Fixed-TAC, a 1 m/s air speed (shown above in Figure 4) almost brought the PAQ up to the levels found in cool and neutral conditions. Figure 6 shows that the significant improvement in PAQ occurred mostly when adding air motion for cooling (right part of the figure shown by a gray bar), not when adding local heating (left part of the figure, shown by a gray bar), although *comfort* was significantly improved for both cooling and heating (Zhang et al. 2008)). Both these observations indicate that it was mainly the air movement, not increased comfort, that enhanced the PAQ.

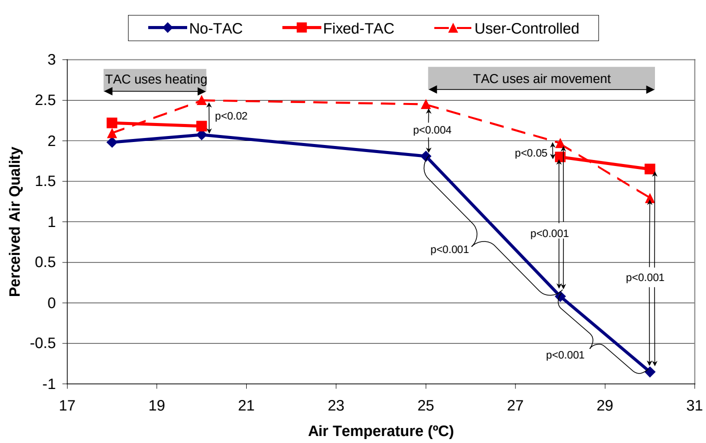


Figure 6. Temperature and air speed effects on perceived air quality

The coincident *comfort* differences were also given above in Figure 4. Like the PAQ, they are larger under still air and smaller at 1 m/s. We might therefore examine the relationship between PAQ and comfort.

Figure 7 presents the relationship between PAQ and thermal comfort. The No-TAC data give averaged results of tests with no air movement, under 5 test conditions (18, 20, neutral, 28, 30ºC). The figure shows that PAQ was almost constant across different levels of comfort when the air temperature was from cool to neutral (18ºC to neutral), but linearly decreased with decreasing comfort as the air temperature rose from neutral to warm (neutral to 30ºC). User control (which contributed the TAC's heating and cooling along with a sense of personal control to the No-TAC situation) significantly increased comfort and PAQ for almost all the equivalent points. The Fixed-TAC (contributing heating and cooling but not the sense of control) increased comfort and PAQ significantly over No-TAC for the 28 and 30ºC temperatures, but not significantly for the 18 and 20ºC temperatures.

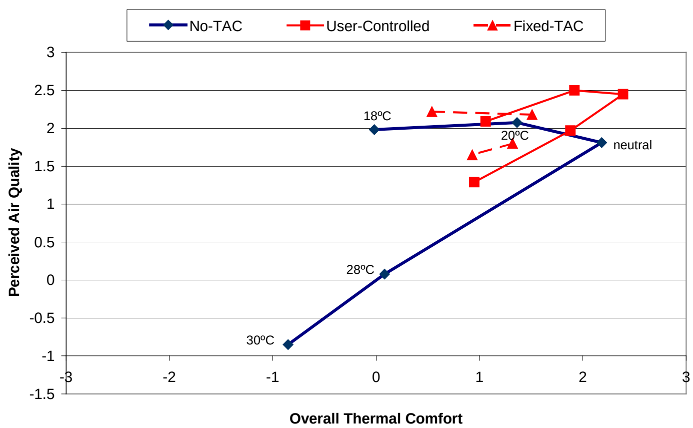


Figure 7. Comfort and perceived air quality under still air

In conclusion: *air movement* by itself affects PAQ, and *thermal comfort* may affect (or be affected by) PAQ under warm still-air conditions.

Dry-eye discomfort and air movement preference

We designed the head ventilation nozzles to supply air from the side into the occupant's breathing zone, for two reasons: to avoid dry-eye discomfort, and to avoid draft discomfort which is most likely for air impinging on the back of the neck. The survey results shown in Figure 8 demonstrate that the air movement at the 28 and 30ºC did not cause dry-eye discomfort. In the left figure, the lines including the head ventilation device are very similar to the No-TAC line without the device. In general, the eye-dryness comfort was lower when the air temperature was warmer.

With the air speed 1 m/s in the breathing zone at warm temperatures (middle figure, again the two TAC lines), the air movement was judged acceptable. Still air was not acceptable in the warm environments (No-TAC line).

The air movement preference shown in the right figure indicates that with 1m/s at the breathing zone under warm environments (TAC lines), people preferred 'no change' (didn't want the air movement slower). In still air (No-TAC line), people preferred more air movement, in both the warm environments *and* the neutral one.

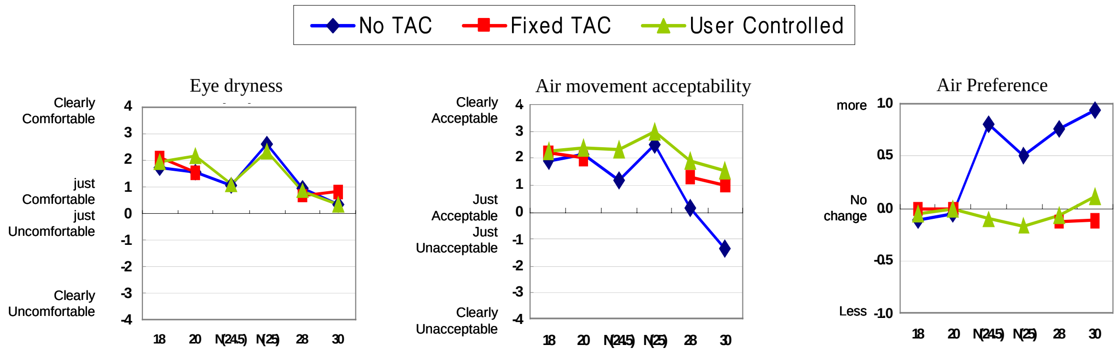


Figure 8. Dry-eye discomfort, air movement acceptance and preference

DISCUSSION

1) Fang et al. (1998) fitted a model in which PAQ was inversely related to temperature. Under still air conditions, our data supports such a relationship only for temperatures ranging from neutral to warm. Because our PAQ did not decrease further from neutral to cool, we cannot conclude that the lower the air temperature, the better the PAQ.

2) Humphreys et al. (2002) found that PAQ is mostly related to thermal comfort, as opposed to air temperature. PAQ was the best under thermally neutral conditions. When people preferred to be either warmer or cooler, PAQ was lowered, with a stronger reduction when people preferred to be cooler. Our study supports part of this finding by showing a linear relationship between PAQ and comfort in neutral and warm comfort. However, our PAQ is constant as people become cooler-than-neutral, differing from Humphreys' finding.

3) The results from our study demonstrate that air movement not only provides comfort, but it also significantly improves PAQ. How air movement physically causes PAQ to get better is not clear. The air movement effect might come from disrupting the thermal plume around the occupant's body, which contains bioeffluents and tends to be more noticeable when the body is warm or hot. Alternatively, a subjective association of air movement with ventilation and with outdoor breezes might be causing people to associate air movement with better air quality. It could also be true that the air movement improves comfort, which, as in Humphreys' finding, might cause people to feel better about PAQ.

CONCLUSION

1) Perceived air quality was significantly improved by providing air motion, even if it was re-circulated room air. The impact from 1 m/s air movement on PAQ was about equivalent to reducing the temperature from warm (28ºC) and hot (30ºC) to a neutral environment at 24.5 ºC. The PAQ decreased with rising air temperature under neutral to warm conditions. It is almost constant from neutral to cool conditions.

2) There was no dry-eye discomfort with the head ventilation device as designed. People accepted the air movement when it was 1 m/s around the breathing zone. People expressed a preference for more air movement in neutral and warm conditions when the TAC devices were off.

ACKNOWLEDGMENTS
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