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### Title

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# Comfort, Perceived Air Quality, and Work Performance in a Low-Power Task-Ambient Conditioning System

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## ABSTRACT

Zhang's thermal comfort model [1] predicts that the local comfort of feet, hands, and face predominate in determining a person's overall comfort in warm and cool conditions. We took advantage of this in designing a task-ambient conditioning (TAC) system that heats only the feet and hands, and cools only the hands and face, to provide comfort in a wide range of ambient environments. Per workstation, the TAC system uses less than 41W for cooling and 59W for heating. We tested the TAC system on 18 subjects in our environmental chamber, at temperatures representing a wide range of practical winter and summer conditions (18-30°C). A total of 90 tests were done. We measured subjects' skin and core temperatures, obtained their subjective responses about thermal comfort, perceived air quality, and air movement preference. The subjects performed three different types of tasks to evaluate their productivity during the testing. The TAC system maintains good comfort levels across the entire temperature range tested. TAC did not significantly affect the task performance of the occupants compared to a neutral ambient condition. Whenever air motion was provided, perceived air quality was significantly improved, even if the air movement was re-circulated room air. In our tests, subjects found thermal environments acceptable even if they were judged slightly uncomfortable (-0.5). By reducing the amount of control normally needed in the overall building, the TAC system saves energy. Simulated annual heating and cooling energy savings with the TAC system is as much as 40%.

## KEYWORDS

Personal environmental control, task-ambient conditioning, personal ventilation, comfort, perceived air quality, energy efficiency

## BACKGROUND

Office occupant surveys show that thermal discomfort is a major cause of dissatisfaction with office environments [2], and is linked with occupants' perceived work productivity [3]. Surveys have also shown that providing occupants with personal control of temperature and air movement enlarges the range of ambient temperatures in which they are comfortable [4, 5]. Other surveys suggest that increased air movement improves occupants' perceived air quality [6]. Finally, a laboratory study has demonstrated that in warm conditions, the comfort of the head and hands dictates a person's overall discomfort; in cool conditions, the comfort of the feet and hands dictate overall discomfort [7, 1]. These results suggest that a personally controlled task-ambient system (TAC) that focuses directly on these body parts may efficiently improve comfort in office environments.

We should note here that TAC systems are interchangeably known as 'personal environmental control systems' (PEC), and sometimes also as 'personal ventilation systems'.

## OBJECTIVES

The study was designed to:

- Examine the ability of a low-power task-ambient conditioning system to maintain comfort over a wide range of ambient room temperatures.
- Explore productivity effects associated with this type of task-ambient conditioning.
- Examine how the presence of personal control affects comfort.
- Examine connections between air speed near the face and the perception of air quality.
- Quantify this TAC system's ability to reduce overall building energy use.

## METHODS

### 1. TAC system design

Figure 1 shows the four TAC devices. A conductive hand warmer and a radiant foot warmer heat occupants' extremities in cool (winter) conditions. For summer conditions, a head-ventilation device cools the head by air motion, and a hand-cooling device operates through conduction and air motion. Electricity use of the TAC system and environmental parameters were measured. The system's peak wattage for cooling is 41W, and for heating at steady state is 59W.

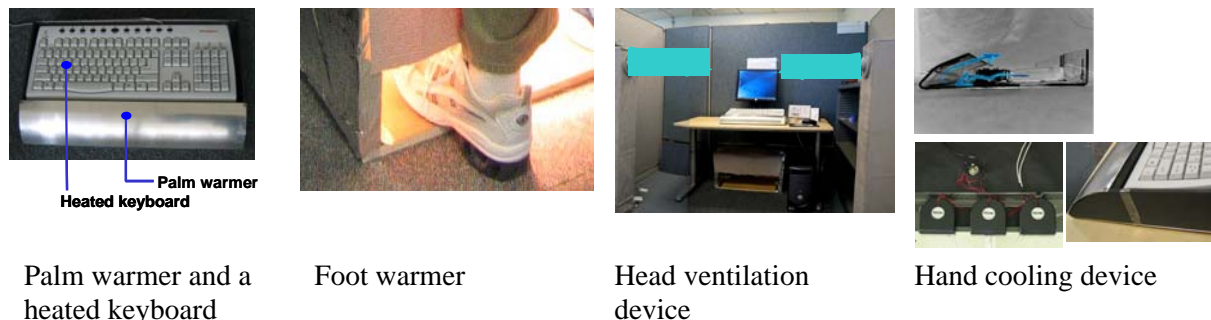


Figure 1. Four TAC devices

**Palm warmer:** The palm warmer is a curved surface of highly conductive aluminum. Electrical heating tapes under the aluminum warm the palm surface quickly and efficiently. The typical surface temperature is 35°C, and power consumption 26W. In our prototype, the keyboard is raised 4 cm, and we lowered the table accordingly. The shape is similar to that of a common commercial keyboard with a raised soft area under the palm. We did not evaluate whether of the raised keyboard was ergonomically different from more typical keyboards.

**Hand ventilation device:** The palm warmer is at the front edge of a tray holding the keyboard. Beneath the keyboard but within the tray there are small fans (6W total). The fans draw air from the back

of the keyboard tray, and direct it through a small gap between the keyboard and the palm warmer to cool the hands.

**Foot warmer:** This is a well-insulated box with a reflective foil lining inside, and a curtain in front to contain warm air. There is a 125 W reflector heating lamp focusing on the top of the feet. Partial heating rates are created by cycling the lamp. At room air 18°C, our subjects selected an average radiant flux of 30W and an internal air temperature of 32 °C.

**Head ventilation device:** Two 5-cm (2-inch) diameter air supply nozzles on the sides of the workstation are aimed at the occupant’s cheeks and breathing zone, 0.6 m (2 ft) away. The nozzles are connected to a local fan (35W) providing either cool air or re-circulated room air. Re-circulated room air is drawn from the chamber’s underfloor plenum which is open to the chamber above through large grilles around the chamber perimeter. Cooled supply air is 100% outside air coming through the chamber’s HVAC system. . The two nozzles in each workstation together provide a maximum of 24 L/s air. The maximum outlet velocity from the head ventilation device at the outlet is about 6 m/s, reducing to around 1 m/s by the time it reaches the vicinity of the cheek. Because air movement could cause dry-eye discomfort [8, 9] we designed the head ventilation system so that the air does not blow directly onto the face and eyes.

## 2. Subject test conditions

We conducted subject tests to evaluate comfort consequences of the system across a wide range of winter and summer conditions (18-30°C, table 1). Eighteen subjects (9 male and 9 female) participated in each of the 5 test conditions listed in Table 1, for a total of 90 tests.

*Table 1. Measured average chamber air temperatures and effective temperatures*

	Room air temperature	Effective temperature (ET*)
hot	30.0°C (86.0°F)	29.0°C ±0.1
warm	28.0°C (82.4°F)	27.5°C ±0.1
neutral	25.0 or 24.5 °C (77.0°F or 76.1°F)	24.2°C ±0.1
cool	20.0 (68.0°F)	19.9°C ±0.1
cold	18.0 °C (64.4°F)	18.0°C ±0.1

Two workstations were installed in the Controlled Environment Chamber at UC Berkeley so that two subjects could be tested at the same time (Figure 2). The chamber size is 18 x 18 ft, with windows on two sides. The room is controlled by a 2 x 2 ft ceiling diffuser, and the air is exhausted at the edge of the ceiling. The air supply from the diffuser to the chamber is 100% outside air, with a 4.6 ACH air change rate. The subjects were supplied standardized clothing with summer (0.5 clo) and winter (0.6 clo) levels.



Two subjects with winter clothing (.66 clo)



Subject with summer clothing (.5 clo)

Figure 2. Experimental set up

Each test included three control strategies for operating the TAC system: 'No TAC', 'Fixed TAC', 'User Control'. 'No TAC' means none of the TAC features are enabled. 'Fixed TAC' means that the TAC settings are fixed at levels prescribed by the experimental design. Under 'User Control', the subjects were allowed to adjust the heating levels of the palm warmer and foot warmer, or the air speeds of the head and hand ventilation devices for cooling. The researchers alone adjusted the nozzle direction, done before each test, based on the height of the subject. The nozzles are about 0.6 m away from a subject's cheeks. The air from the nozzles created a relatively large area of air movement, so the normal position of the subjects did not take them outside of the air movement. Subjects also do not have control over the air temperature from the nozzles.

### 3. Schedule for human subject tests

Each test took three hours, divided into 3 one-hour sessions (Figure 3), 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. For the neutral condition, in which there was no fixed-TAC session, the three-hour test was divided into either of the following two sequences: no-TAC, user-control, no-TAC, or user-control, no-TAC, User-control. Under the neutral condition, we assumed that TAC was not necessary, so there is no fixed-TAC.

The subjects arrived 15 minutes before the test started to change into the test clothing, tape on the skin temperature sensors, and swallow a transducer pill that measures their body core temperatures

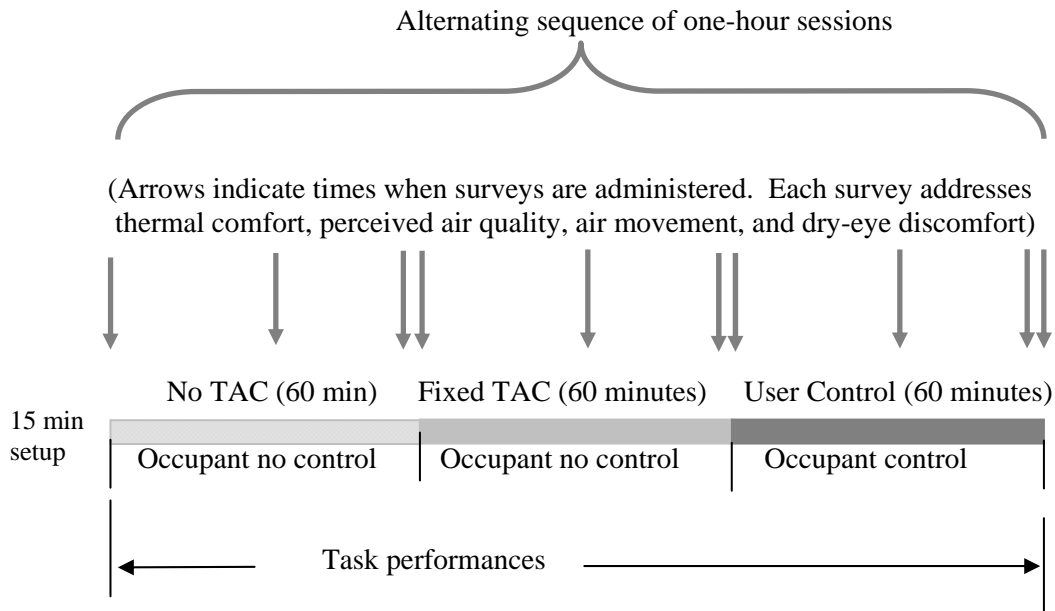


Figure 3. The schedule of sessions and surveys within a 3-hour test

The schedule for each hour is described in Figure 4. The surveys and subjects' tasks (sudoku, math, and typing; described later) were all pre-scheduled into the computers that the subjects worked on, so they automatically appeared on their screens according to the timeline shown here.

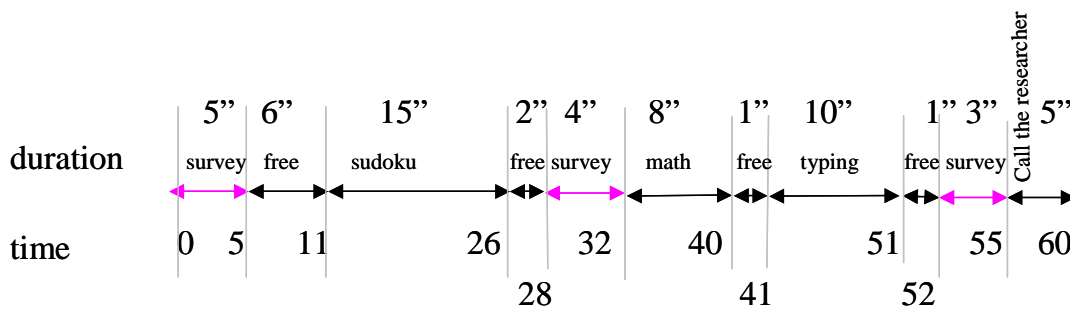
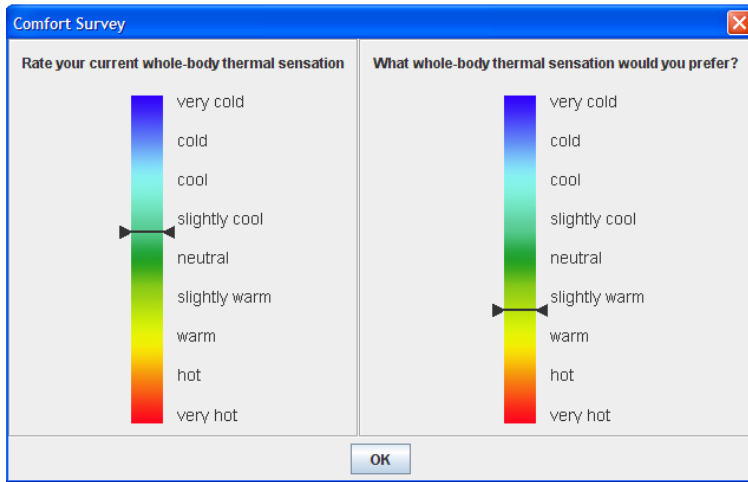


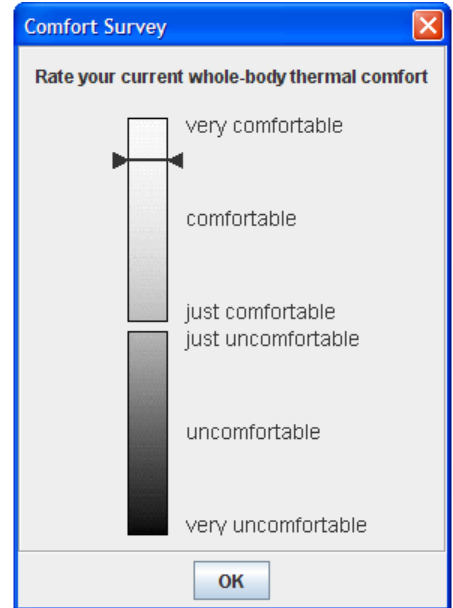
Figure 4. Schedule of tasks performed in each 1-hour test session

#### 4. Subjective surveys

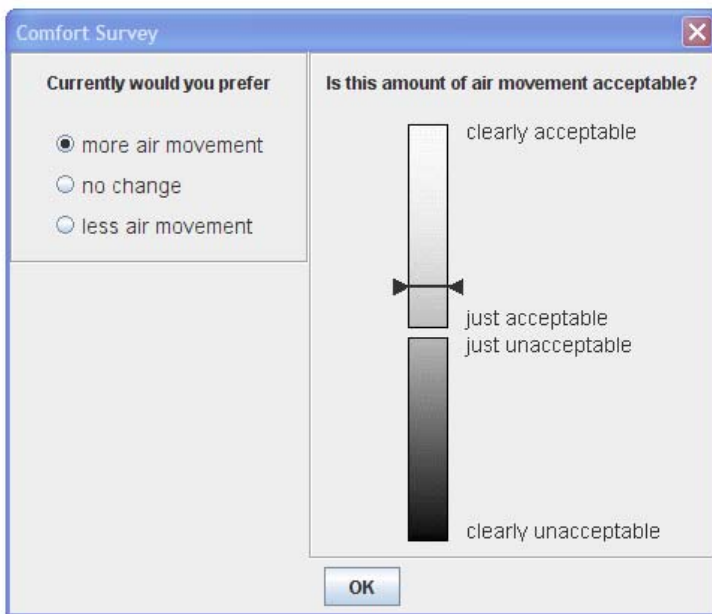
The survey questionnaires are for thermal sensation, comfort, acceptability of the thermal environment, perceived air quality, dry-eye discomfort and air movement preference etc. A few are shown in Figure 5. They appeared automatically on the subject's computer screen before, at the middle, and at the end of each one-hour test session. The scales are continuous. The subjects' votes were stored in the computer. A subject typically finished the questions in 2 minutes.



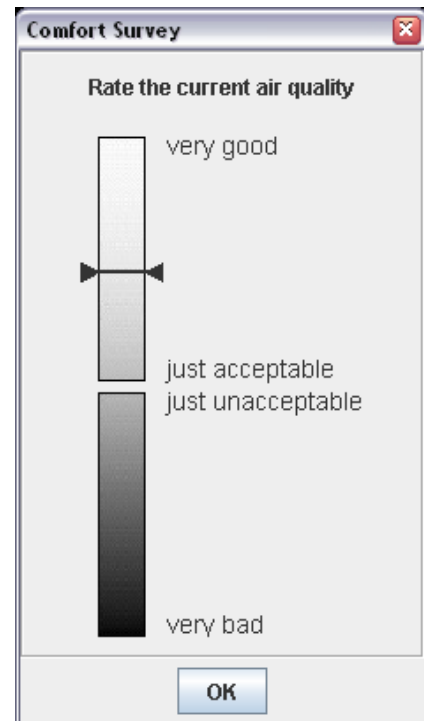
Thermal sensation and preferred thermal sensation questionnaire



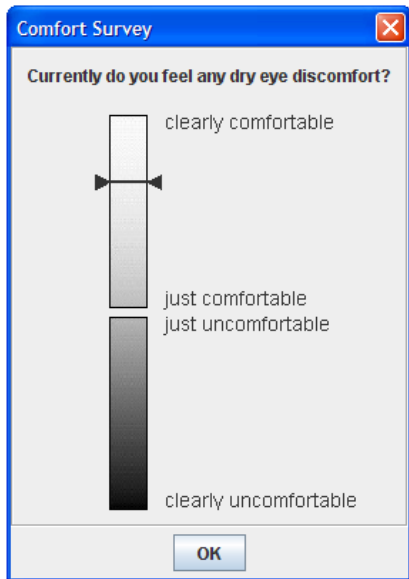
Thermal comfort



Air movement acceptability



Perceived air quality scale



Dry-eye discomfort

Figure 5. Subjective survey questions

We used paired thermal sensation and preferred sensation surveys because this format not only indicates thermal preference (want to be warmer, no change, cooler) by subtracting the two votes, but it also indicates the thermal sensation that a subject prefers, the magnitude of the preference, and whether neutral is the preferred sensation. This scale pairing was first proposed by Griffiths [10], and adopted by Humphreys [11].

## 5. Productivity evaluation

Common approaches to evaluating productivity in laboratory studies include math exercises (normally addition), typing, proof reading, and creative thinking. It often happens in laboratory studies that the differences in the task performances between different environmental conditions are not significant, while in field studies, significant differences are seen [12, 13, 14]. The lack of response in laboratory studies could mean that the environment did not impact productivity. It could also mean that the methods used in the laboratory studies did not properly represent normal office work, or that the motivation of subjects over the short duration of laboratory tests overwhelms environmental influences that in normal life would have an impact on office work. We looked for ways to evaluate task performances (productivity), over a reasonably long time period, involving both mental and dexterity work, and providing resolution in the level of response.

We chose the following three tasks to evaluate work performance, each of which was automated on the computer. The schedule for performing the three tasks in each hour session is shown above in Figure 4.

*Logical thinking:* Sudoku, 15 min. Medium difficulty examples were chosen so that subjects could complete more than one in a session, and not become stuck on any test.



*Mental performance:* Math problems, 8 min. We chose fraction multiplication for the math problems, because the exercises were not tedious but also not too difficult; always solvable but at varying rates of speed depending on how many mental shortcuts are employed.

*Dexterity:* Typing, 10 min. We used commercially available typing training software that automatically scored the speed and accuracy of the typing. Figure 6 shows the screen shot for the three tasks.

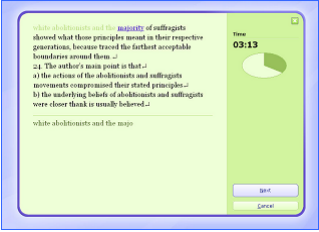
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Figure 6. Tasks performed during the test

At the end of each one-hour test session, we asked the subjects to stretch their bodies during a five-minute break. The researchers also initiated short conversations with them. We also provided a light snack before the start of the next one-hour session, which the subjects could eat if they wished. The break was to prevent subjects becoming tired or sleepy, and the food to prevent subjects becoming low in blood sugar, since we could not standardize the meals they had before they arrived for the tests, and we did not want their productivity to be affected during the three hours of testing. The break also allowed us to observe their reactions to the ambient environment, away from their workstation. The subjects could easily move around during the break because we used wireless sensors measuring skin and core temperatures.

## 6. Subject training sessions carried out prior to testing

All subjects attended training prior to the experimental tests. The training sessions served two purposes. First, the subjects needed to know about the experimental procedures, the nature of the survey questionnaires that they would be answering, and the tasks that they would perform. It was important that they be fully familiar with the experimental activities prior to the first comparative test. The second purpose was to have the subjects practice the sudoku and math problems, so that they were well up on their individual learning curves about these skills before the tests began.

We provided two types of training. The first was a 2.5 hour training session during which we first described the test procedure and survey questionnaires via a Powerpoint presentation. Then we asked the subjects to practice three 15-minute sudoku exercises, and three 8-minutes math solution exercises. After they practiced the sudoku and math, they went to the environmental chamber to visit the work stations and to learn how to use the TAC system controls.

Following this training session, we had the subjects come in twice over two weeks to do example math, sudoku, and typing tests, answer survey questions, and use the TAC systems in the chamber, working just as they would be doing in the real test. After the two weeks, the subjects were thoroughly familiar with

the test procedures and the TAC controls, and had reached a fairly steady state in their skills with the productivity tests.

## **7. Physiological and environmental condition measurements**

We measured skin temperature at 10 locations at 5-second intervals. The core temperature was measured at 20-second intervals by a wireless transducer (a pill, size of a vitamin capsule) which each subject swallowed before the start of a test.

During the tests 3 thermistors in each workstation measured the air temperature at the three standard heights (0.1, 0.6, 1.1m). The sensors are located about 0.7 m away from the subject. Globe temperature and humidity were measured at 1.1 m. Another thermistor measured the air temperature at the outlet of the nozzle, and a thermocouple to measure the surface temperature of the palm warmer. Because the foot warmer was controlled by cycling the heat lamp inside, an illumination-sensor in the warmer monitored the on/off times of the lamp. Measurements were collected in Hobo dataloggers.

The air velocity field in the workstation was characterized before the actual tests, because velocity measurement during testing would have been too intrusive. This was done with a manikin, with the head-cooling air jets set at various velocities. The manikin surface was heated to 33°C to generate a realistic buoyant plume around the person. During the subsequent human subject tests, the experimenters did spot checks of velocity around the head with hand instrumentation, to assure that actual airflows matched the values predicted from the airflow control settings.

## **RESULTS AND ANALYSIS**

### **1. Whole-body thermal sensation**

In the following data analysis, the term “user-controlled” refers to “user-controlled TAC”. Figure 7 presents the 18 subjects’ average whole-body (‘overall’) thermal sensation, for each of the 5 environmental conditions and the three control strategies. From the figure we see that the TAC systems bring thermal sensation almost to the ‘neutral’ level for the 20°C and 28°C air temperatures, and that they bring the sensation at 18°C and 30°C to within ‘slightly cool’ (-1) and ‘slight warm’ (1). No significant difference is seen between the fixed-TAC and the user-controlled strategies. The standard deviation of sensation for the no-TAC and fixed-TAC conditions is around 1 scale unit, and is smaller under the user-controlled condition. This means that by controlling the TAC, people are able to adjust their sensation closer to neutral than when control is absent.

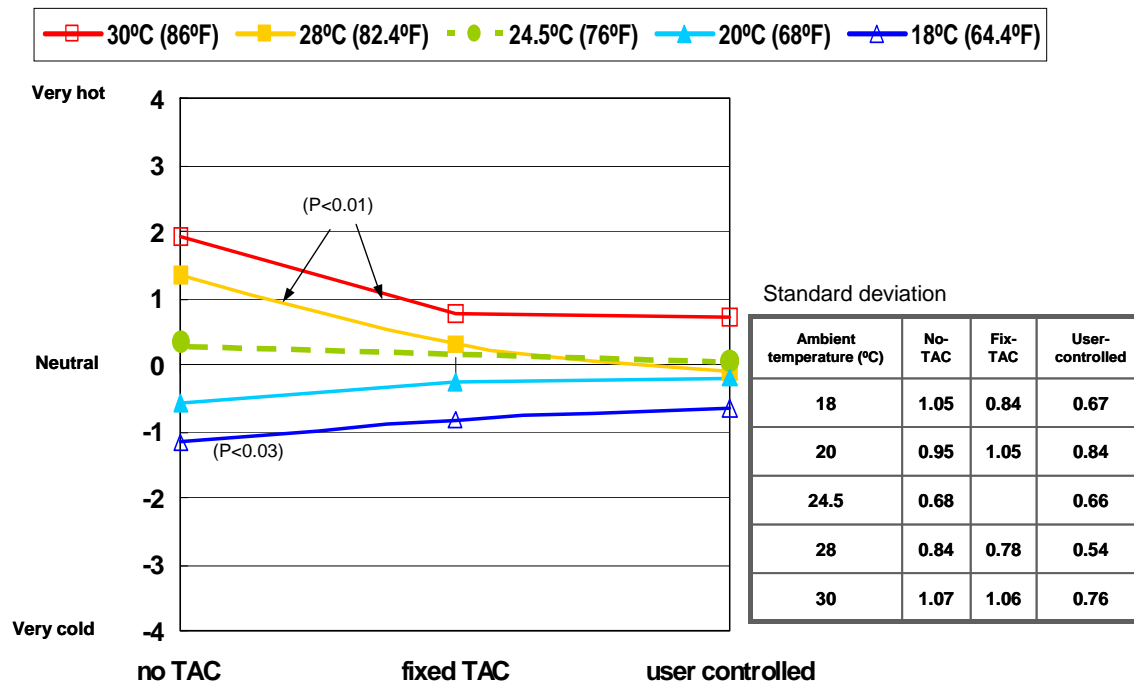


Figure 7. Whole-body thermal sensation

## 2. Whole-body thermal comfort

Comfort was improved by TAC systems in all conditions except one (20°C with fixed-TAC, Figure 8). The TAC systems made people comfortable (comfort scale equal or above 1) over a large air temperature range, from 18°C to 30°C.

The comfort level was slightly higher with user-control than with fixed-TAC, significant at two conditions (28 and 20°C). When the air temperature is as low as 18°C and as high as 30°C, the user-controlled TAC does not provide obvious advantage over fixed-TAC because people's requirements for warmth and coolth are clear and the fixed-TAC can be easily set to fulfill the requirements. It is in the less extreme conditions (in our test conditions, 20 and 28°C air temperatures), that the user-controlled shows significant improvement over fixed-TAC ( $p < 0.05$  and  $0.01$  respectively). People's demand for warmth and coolth is more variable and sensitive in these less extreme conditions.

We found that at the 20°C room air temperature, the palm warmer was often regarded by subjects as unnecessary, and that it could create discomfort from being too warm. The fixed-TAC surface temperature for the palm warmer was less comfortable to subjects in the 20°C environment than in the cooler 18°C environment, creating the dip in the 20°C whole body comfort line. The standard deviation pattern for comfort is similar to that of sensation, except that the magnitude is larger. This suggests that subjects have a harder time determining comfort than their thermal sensation.

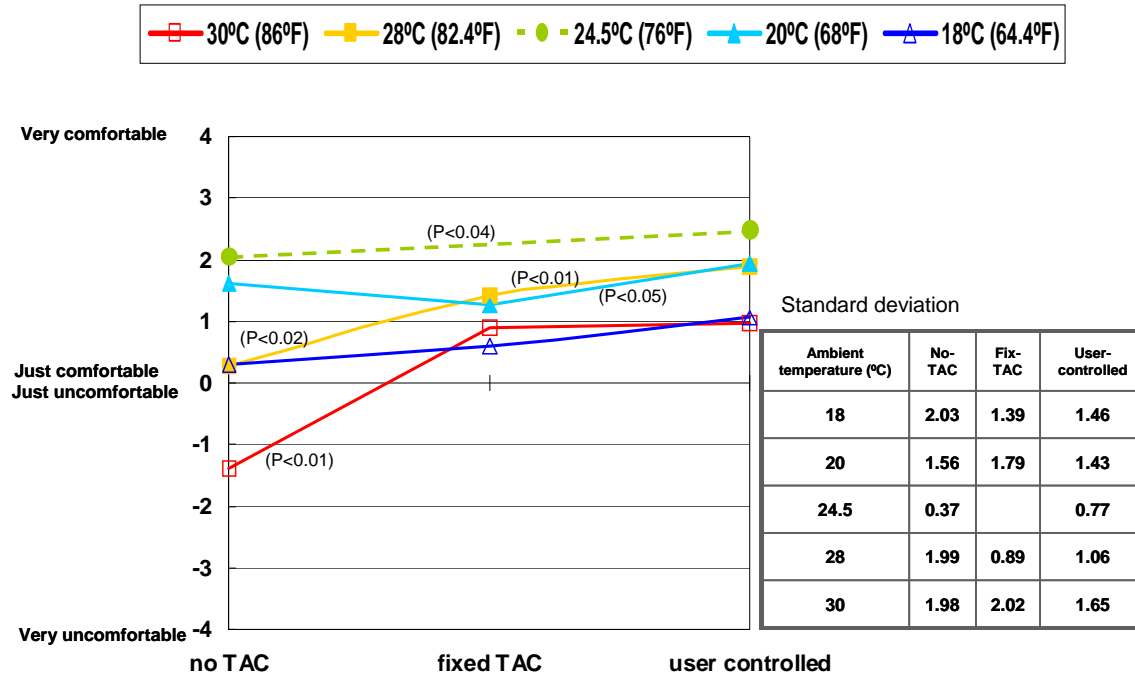


Figure 8. Whole-body thermal comfort

### 3. Acceptability of the thermal environment

Analyzing the thermal environment acceptability with thermal comfort and thermal sensation, the results show that people accept thermal environments when they are slightly uncomfortable (-0.5) and above. The thermal sensations -2 and +2 are the thresholds within which most people are comfortable and accept the environment. For detailed analysis, please see [15].

### 4. Task performance

The levels at which individual subjects performed the 3 different types of tasks are very different. Also, the differences between the subjects are larger than the intrapersonal productivity effects caused by the environment.

We normalized each subject's task scores using the score of the same person under a reference condition, the neutral condition without TAC. The reference score was set as 100% and the other scores were converted into either increases or decreases from the reference. The results for the three task performances are presented in Figure 9.

In general, having TAC produces better performance for sudoku and math (the pink and light blue lines are above the dark blue line in Figure 9). However, the differences are significant at level  $p < 0.05$  only under two conditions, marked by the two dashed boxes in the figure. For Sudoku (logical thinking), performance was better in warm conditions and for the Math (mental performance), performance was better in cool conditions. We were expecting to see that mental performance (sudoku and math) would be better under cool environments. For typing, we might have expected to see improved performance as the

air temperature gets warmer ([16] found this and attributed it to improved dexterity). However, in this test, the differences in typing rate among all the conditions are insignificant. Typing does not appear to be a sensitive method for evaluating performance in this range of environmental conditions. Possibly mental effects act to counteract dexterity effects, but we cannot test this with our data.

It is interesting to see that for sudoku and math tasks, the performance with TAC systems in many cases is better than in the neutral condition (100%). That could be an encouraging sign for the design of non-uniform environments.

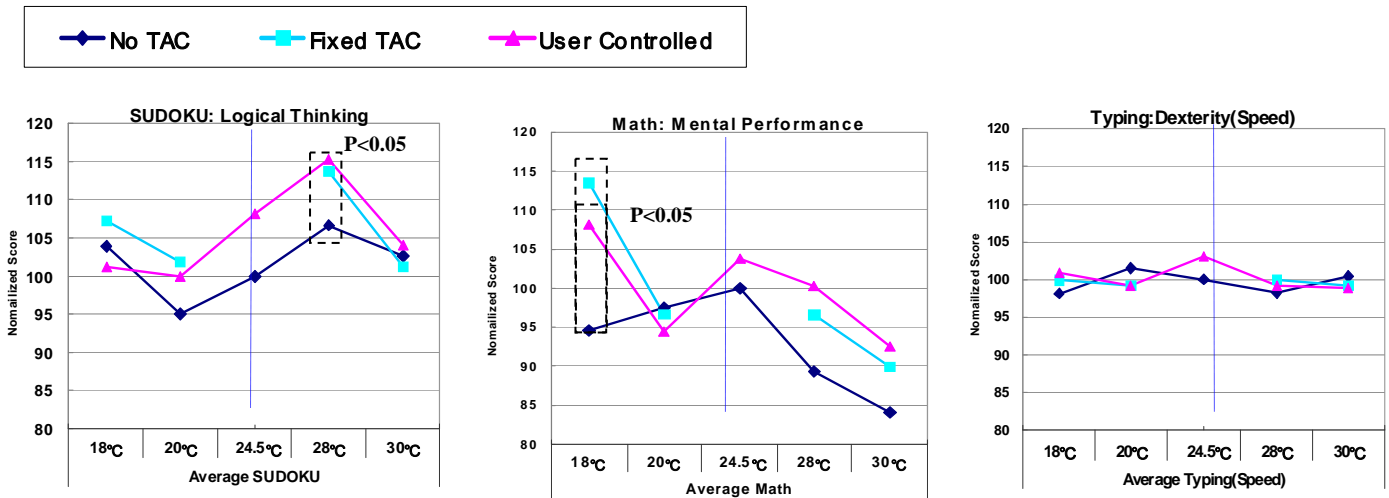


Figure 9. Task performance normalized to the neutral condition

As we saw before with the subjective comfort votes, math performance was unexpectedly low in the 20°C air temperature condition with TAC systems. The same explanation may hold--that the room wasn't sufficiently cold for the high surface temperature of the palm warmer to feel comfortable. From their comments, we know that it bothered some subjects and may have lowered their performance.

It is possible that the task performance under user-control may be lowered because it takes time for subjects to make adjustments to the TAC systems. Over the limited time period of the tasks, this lost time might act to lower the performance scores. We are not able to quantify this potential effect.

## 5. Perceived air quality

Figure 10 allows us to examine how much air movement improved PAQ. Under fixed-TAC, a 1 m/s air speed at the breathing zone almost brought the PAQ up to the levels found in cool and neutral conditions. Figure 10 also 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 (Figure 8). Both these observations indicate that it is mainly the air movement, not increased comfort, that significantly enhanced the PAQ. (for more detailed results, see [6])

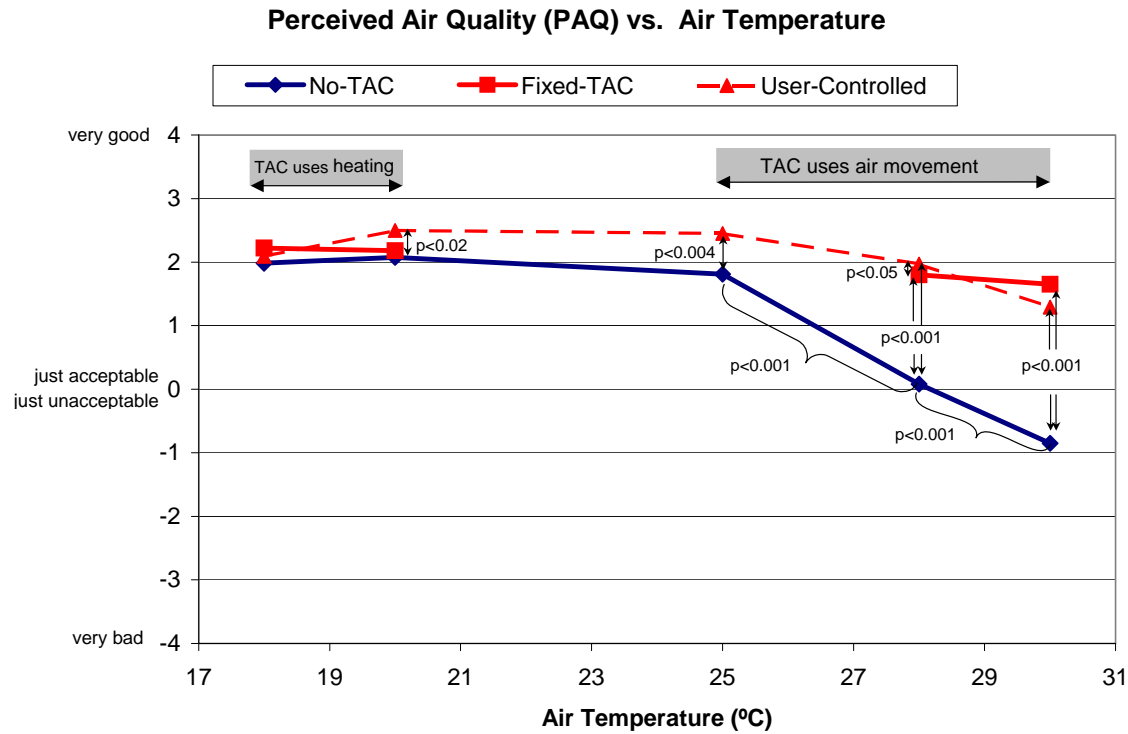


Figure 10. Temperature and air speed effects on perceived air quality

## 6. Dry-eye discomfort and air movement preference

We designed the head ventilation nozzles to supply air into the occupant’s breathing zone from the side, for two reasons: to avoid dry-eye discomfort, and to avoid draft discomfort. The survey results shown in Figure 11 demonstrate that the air movement at the 28 and 30°C did not cause any dry-eye discomfort. In the left figure, the lines including the head ventilation device are similar to the no-TAC line without the device. In general, the eye-dryness comfort was significantly ( $p < 0.05$ ) 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 significantly ( $p < 0.05$ ) less acceptable in 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.

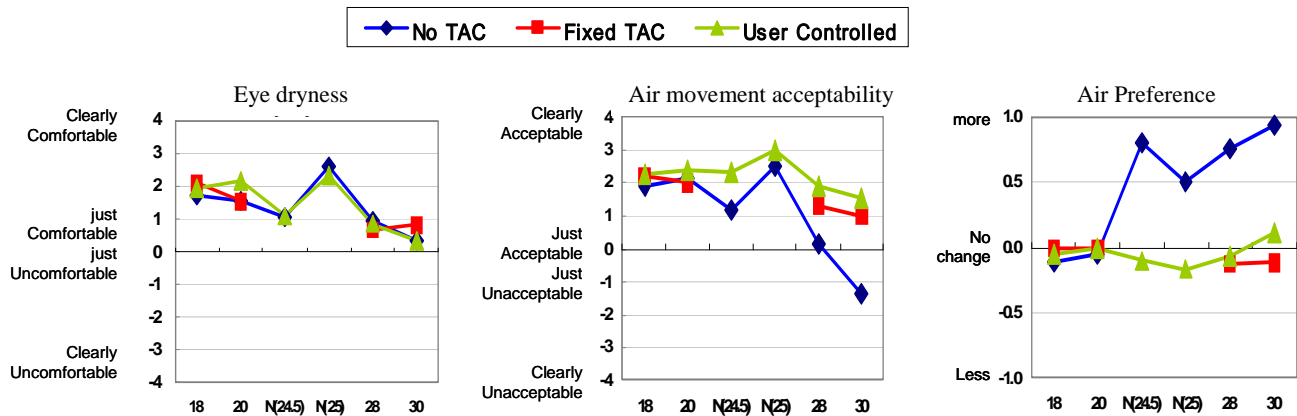


Figure 11. Dry-eye discomfort, air movement acceptance and preference

## 7. Body temperatures

Generally, whole-body comfort follows the changes in local body comfort. Under our 5 test conditions, we found the skin temperatures associated with highest comfort to be:

- Cheek: 32.5 – 33.5°C, found in the neutral condition tests
- Finger: 30.6 - 32°C, found in the neutral condition tests
- Foot: 33.15°C, found in the 20°C User-Controlled tests and in the neutral condition tests

These temperatures might be useful for the design and control of TAC systems.

## 8. Comparing the energy use of the TAC system with that of a conventional HVAC system

The energy use of the TAC system is here compared to a conventional HVAC system in Oakland (a mild coastal climate), Fresno (Central Valley climate, hotter in summer and colder in winter), and Minneapolis (hot in summer, very cold in winter). The simulations were performed using EnergyPlus/DesignBuilder. For more detailed results, See [15].

### (A). Measured energy use of TAC systems

We measured the power consumption of each of the four TAC systems under tested conditions. Following figures (Figure 12 and 13) present the energy consumption for cooling and heating.

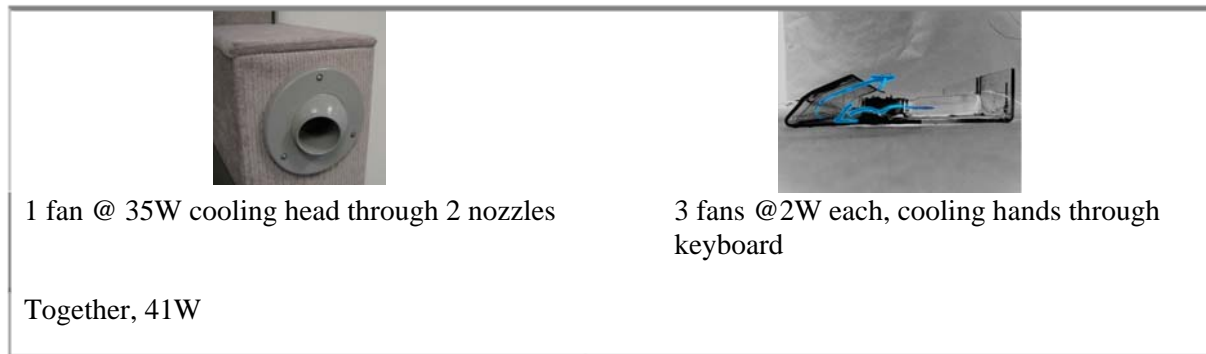


Figure 12. Summer Condition (Cooling Mode): measured energy use for cooling

We did not estimate the energy required to cool the TAC supply air to 24 °C (for the 30 °C ambient condition). In that condition, the air from the nozzles was so mixed with the air in the room that we came to the conclusion that the low supply air temperature was not a major factor in the comfort provided by the jet, but the air movement is. In an actual building design, the TAC could have had a similar comfort effect using re-circulated air from the room, so it would not be necessary to use energy to cool the TAC air.

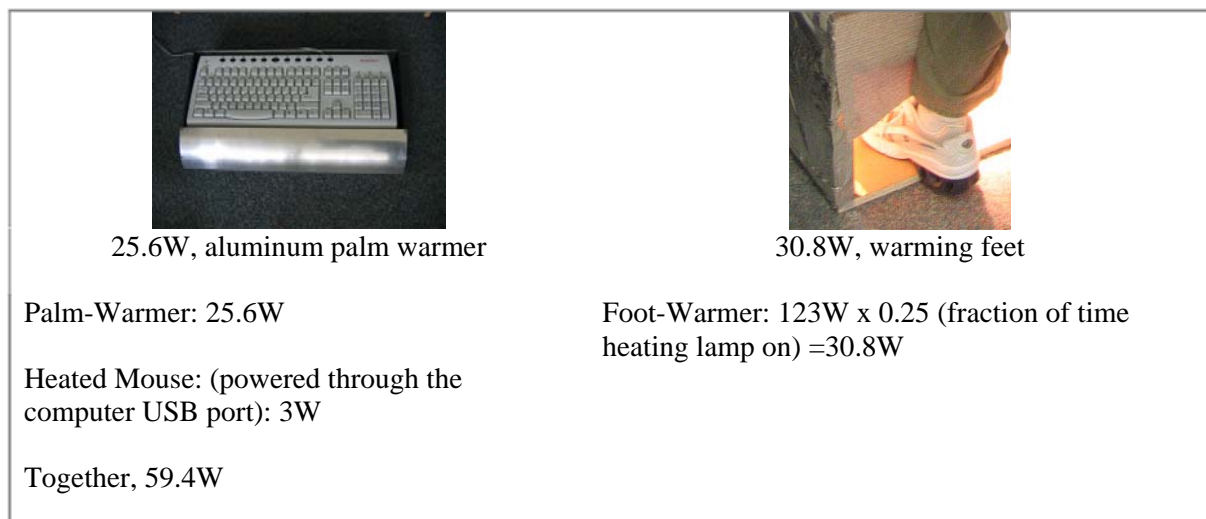


Figure 13. Winter Condition (Heating Mode at 18°C) air: measured energy use for heating

As described earlier, our commercially obtained heated keyboard was not effective at heating the hand, and the hand heating from the experiments derived almost entirely from the palm-warmer and the heated mouse. Therefore, in this analysis we exclude the energy used by the keyboard from the energy required to obtain the levels of heating observed in our human subject test.

## (B). Simulating the energy savings of a TAC-equipped building

### (a). Description of the building and energy simulation approach.

The comparison building is 90 x 60m, with three stories. Each floor plate is 5,400 m<sup>2</sup> (usable area 5,312 m<sup>2</sup>/story). The glazing area is 30% of the wall area. Each floor consists of five zones of open office plan, with the perimeter zones 4.5m in depth.



The occupant density is 0.04 persons/m<sup>2</sup>. Internal loads include 8.07 W/m<sup>2</sup> computer heat gain, and 10.76 W/m<sup>2</sup> (200 lux) lighting. Infiltration is assumed to be 0.85 air changes per hour.

In this paper we term the indoor temperature range between thermostat calls for heating and cooling a 'dead-band', as in dead-band thermostats. The conventional building has VAV with terminal reheat, maintaining a room air temperature dead-band of 21.5 – 24 °C. Mechanical ventilation provides fresh air at 7.1 l/s per person (15cfm). Heating is by gas boiler and cooling by an electrical chiller. The TAC building has the same HVAC system and ventilation rate, but the ambient conditions are controlled to two different dead-bands: 20 – 28°C, and 18 – 30°C. As presented in Figure 11, occupant comfort is well-maintained in all these temperature ranges. The palm-warmer and the foot warmer are added to each workstation for heating, and the head and hand ventilation devices for cooling. The total energy is the sum of ambient HVAC energy and local TAC energy.

The energy use for a conventional HVAC system is the energy used to keep the indoor air temperature within 21.5 – 24°C.

The energy use of the TAC plus HVAC system consists of two parts. The first is the HVAC energy used to keep the indoor air temperature within 20 – 28°C or 18 – 30°C. The energy needed to maintain each of these ranges was simulated by EnergyPlus. The second part is the energy used by all the individual TAC systems at the workstations. When the air temperature is within 21.5 – 24°C, no TAC is applied.

In our calculations, we assumed 80% workstation occupancy. Bauman et al. [17] measured 70% average occupancy in an office field study. Since TAC systems are automatically turned off when there is no occupant, this mode of occupant-sensitive environmental conditioning produces significant energy savings.

One might ask whether the hottest and coldest ambient conditions would be acceptable for office workers when they are not at their workstations. In our tests, our subjects took a five-minute break between each one-hour session. During the breaks the subjects left their workstations and were exposed to the ambient condition. There was no discomfort noted, either in the hot or cold conditions. Comfort at the workstations therefore persists for a length of time, but we did not examine this beyond five minutes. This might be a reasonable time period for going to copy machines, bathroom, etc., but it would be useful for future TAC design to obtain statistical data for both the length of typical breaks and the occupants' reactions to them.

(b). Floating indoor air temperature without heating or cooling.

Expanding a dead-band produces savings in two ways: it reduces the temperature difference between the set points and the building's floating temperature, and it reduces the number of hours per year needed for mechanical conditioning. Some of the savings of TAC systems will come from the opportunity to use unconditioned outside air--through economizer or natural ventilation--to satisfy the wider ambient temperature dead-bands that TAC enables.

(c). Seasonal energy consumption calculations.

The energy consumption of the conventional and TAC systems is usefully compared on a seasonal basis, to clarify when the performance differs and why. The summer and winter seasons are each 3 months long. The simulation results are presented in Table 2. The heating and cooling HVAC energy is as measured on site.

Table 2. Seasonal site energy use of the TAC+HVAC system, compared with a conventional HVAC system

System type	Fresno		Oakland		Minneapolis	
	summer	winter	summer	winter	summer	winter
Conventional HVAC (kWh)	324,038	169,832	183,174	115,004	238,826	566,956
<b><u>TAC system, dead-band 18 – 30°C</u></b>						
Ambient conditioning (kWh)	224,884	51,025	97,197	42,105	141,622	370,641
(% of Conventional HVAC)	69.4%	30.0%	53.1%	36.6%	59.3%	65.4%
Local task conditioning: heating (kWh)	0	873	0	30	0	16,790
(% of Conventional HVAC)		<b>0.50%</b>		<b>0.03%</b>		<b>2.96%</b>
Local task conditioning: cooling (kWh)	13,592	8,239	13,801	10,371	13,801	585
(% of Conventional HVAC)	<b>4.20%</b>	<b>4.90%</b>	<b>7.53%</b>	<b>9.02%</b>	<b>5.78%</b>	<b>0.10%</b>
Local+ambient system (kWh)	238,475	60,136	110,997	52,506	155,422	388,017
(% of Conventional HVAC)	<b>73.6%</b>	<b>35.4%</b>	<b>60.6%</b>	<b>45.7%</b>	<b>65.1%</b>	<b>68.4%</b>
Savings of TAC system versus conventional HVAC	<b>26.4%</b>	<b>64.6%</b>	<b>39.4%</b>	<b>54.3%</b>	<b>34.9%</b>	<b>31.6%</b>
<b><u>TAC system, dead-band 20 – 28°C</u></b>						
Ambient conditioning (kWh)	255,564	79,836	116,575	54,775	169,055	422,821
(% of Conventional HVAC)	78.90%	47%	63.64%	47.63%	70.77%	74.58%
Local task conditioning: heating (kWh)	0	1,023	0	30	0	16,880
(% of Conventional HVAC)		<b>0.60%</b>		<b>0.03%</b>		<b>2.98%</b>
Local task conditioning: cooling (kWh)	13,592	5,771	13,801	12,128	13,780	314
(% of Conventional HVAC)	<b>4.20%</b>	<b>3.40%</b>	<b>7.53%</b>	<b>10.54%</b>	<b>5.77%</b>	<b>0.06%</b>
Local+ambient system (kWh)	269,156	86,630	130,375	66,933	182,835	440,015
(% of Conventional HVAC)	<b>83.1%</b>	<b>51.0%</b>	<b>71.2%</b>	<b>58.2%</b>	<b>76.6%</b>	<b>77.6%</b>
Savings of TAC system versus conventional HVAC	<b>16.9%</b>	<b>49.0%</b>	<b>28.8%</b>	<b>41.8%</b>	<b>23.4%</b>	<b>22.4%</b>

One can see that the TAC-assisted HVAC system uses between 17 to 65% less seasonal energy to maintain its broader dead-bands than the narrower conventional dead-band. The savings come mostly from the ambient HVAC, since the TAC local heating components use less than 3% of the conventional HVAC use, and cooling components less than 11%.

(d). Annual energy savings from TAC systems.

The total annual HVAC consumptions and savings attributed to TAC at the two interior temperature dead-bands is presented in Table 3. The savings are greatest in Oakland’s milder climate, where natural ventilation can be used most frequently. Savings are roughly the same in Fresno and Minneapolis.

Table 3. Annual HVAC energy saving of TAC system

Interior temperature range	Annual Saving		
	Fresno	Oakland	Minneapolis
18 - 30°C	38%	44%	39%
20 - 28°C	27%	34%	29%

## DISCUSSION

- 1) The analysis of *acceptance and comfort* shows that people accept environments even when they are feeling slight discomfort. Aggregating all our tests, our subjects on average accepted the thermal environment when their comfort was -0.5 (on the uncomfortable side of the comfort scale) and above. Their acceptance of discomfort was less when they did not have access to TAC (comfort scale -0.2 and above).

Our TAC system improves comfort in the three important body parts (head, hand, foot) identified by Zhang [3]. Other systems have been designed that impact other body parts. Zhang and Zhao [18] tested a fixed-TAC system that provided local cooling to the face, chest, and back. Under test conditions neutral and warmer, using the same sensation, comfort, and acceptance scales, their results show that the threshold of acceptance corresponded to comfort of -0.14 (calculated from the regression equation in the paper [18]). This value is close to our no-TAC result, but not as low as our result with fixed-TAC. The difference could be that the three local body parts impacted by our TAC design are more effective at influencing people’s acceptance of thermal environments.

- 2) The thresholds of *thermal sensation* for acceptance and comfort above zero is about -2 to 2. These results in general match the studies from the literature. Data from Gagge et al. (1967; discussed in McIntyre 1980 and Wang et al. [19]) found that sensation -1.5 and 2 are the thresholds ensuring comfort. Wang et al. [19] found that for keeping comfort above zero, the thresholds for sensation are -1.3 and 1.8. Again, under test conditions neutral and warmer, Zhang and Zhao [18] show that for *acceptance* above zero, the threshold for warm sensation is 1.4; for *comfort* above zero, the sensation threshold is 1.27. Their results agree with ours that the range of thresholds for acceptance is slightly wider than the range of thresholds for comfort.

- 3) *User control.* In the more extreme test conditions (18 and 30°C), there was no significant improvement in comfort with user-controlled over fixed-TAC. We were able to select control settings for the TAC system that worked well for our test subjects. This appears to be easier to do when people clearly need warming (at 18°C) and cooling (at 30°C). In the less extreme conditions (20 and 28°C in our test), the degree of heating and cooling appeared to differ among subjects and the user-controlled TAC was rated more comfortable than fixed-TAC. This finding does not support the contention that “being able to control” contributes substantially to occupants’ comfort [4, 5]. If this were true, we would expect to have seen significant improvements in all our user-controlled test conditions.
- 4) For perceived air quality, Fang et al. [20] found that PAQ is better in cooler environments. Our data supports this finding only when the environment is neutral to warm. Because our PAQ does not decrease with air temperature from cool to neutral, we cannot conclude that the lower the air temperature, the better the PAQ. Humphreys et al. [21] found that PAQ is mostly related to thermal comfort. PAQ was the best under neutral conditions. When people preferred to be either warmer or cooler, the PAQ was lowered, with a stronger reduction when people preferred cooler. Our study supports part of this finding by showing a very linear relationship between PAQ and comfort in neutral and warm environment. However, the PAQ decrease as people become cooler than neutral is insignificantly small, which is different from Humphreys’ finding.
- 5) The results from our study demonstrate that air movement not only provides comfort, it also significantly improves PAQ. How air movement physically affects PAQ is not clear. The air movement might be disrupting the thermal plume around an occupant’s body, or an association with ventilation and outdoor breezes might be causing people to associate perceived 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 the PAQ.
- 6) Wang et al. [19] found that 30°C was the finger temperature threshold below which whole-body cool discomfort begins. Our study found that at finger temperature 30.6 – 32, the whole body and finger experienced the highest comfort.
- 7) Although the results are not statistically significant, we did observe that for Sudoku and math tasks, the performance with TAC systems was frequently better than in the neutral condition. In an early study [7], we showed that people’s comfort is better under some transient and non-uniform conditions than the uniform neutral condition. From both types of studies, we see that non-uniform or transient conditions do not necessarily reduce comfort and task performance. That is an encouraging sign for the use of non-uniform environments in office environments.

## CONCLUSIONS

- 1) Comfort was well-maintained at an acceptable level (comfort above 1) in wide range of room temperatures (18 – 30 °C) by a TAC heating and cooling system. Our ventilation cooling devices seemed to be more effective at improving comfort than our heating devices.
- 2) The non-uniform environments provided by the TAC devices did not lower the task performance of the occupants. In fact, under some TAC conditions, performance was better than under the neutral condition. Two conditions produced significant improvements in Sudoku and math. Typing showed no significant difference across all the tests.
- 3) 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 (28°C) and hot (30°C) to a neutral environment at 24.5 °C. The PAQ

decreased with rising air temperature under neutral to warm conditions. It is almost constant from neutral to cool conditions.

- 4) 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.
- 5) The acceptable thermal sensation levels were about from -2 to 2.
- 6) Instead of air-conditioning the entire room to a tight dead-band, the TAC system focuses on the three most influential local body parts, while using HVAC to condition the room to a wider dead-band. This can be done very efficiently compared to conventional systems. For our three test cities, the annual HVAC energy saving is approximately 40% for the wider 18 – 30°C ambient dead-band, and 30% for the narrower 20 – 28°C one.

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