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Assessment of Indoor Environments

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Assessment of Indoor Environments

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I. INTRODUCTION

The energy and environmental consequences of conditioning buildings are immense, and becoming more so around the world. In the United States, buildings consume 38% of the nation's energy consumption, a larger amount than the industrial, transportation, or agricultural sectors. In the global context, the U.S. currently consumes 25% of the world's energy, meaning that 10% of the world's energy is being used in U.S. buildings! About 80% of this building use is for heating, cooling, ventilating, and lighting. The huge construction boom in China, India, and the developing countries is rapidly increasing these countries' need for energy. If their new buildings were to have the same efficiency as the U.S. building stock, the global impacts will be severe. At this point there is little evidence that they will be appreciably different.

The engineering and architecture professions need to invest maximum creative effort into improving the efficiency by which our indoor climates are produced. There are two main components to the energy use problem in buildings: the buildings themselves (their architectural form and their environmental conditioning systems) and the people who occupy and operate the buildings.

Buildings need to be designed and operated to supply indoor climate as needed, but not more (or less). As much as possible of the climate tempering should come from naturally occurring sources, to reduce the energy consumed through equipment and lights. Energy-intensive conditioning should be locally confined, if possible, to where the occupants are. This has been very difficult to do in the past, but with recent developments in ubiquitous wireless sensing and actuating, some of this is becoming feasible.

We also need more sophisticated models of occupant needs and behavior, again so that climates are controlled as needed: when, where, and how much. Occupants are active, mobile, transient, and they inhabit 'memory space'—their recollections of experiences persist and color their sense of satisfaction. Occupants also respond to various forms of feedback about their environment—it may be possible to encourage their involvement with the indoor environment and promote beneficial modes of behavior.

In achieving such improvements, the monitoring and assessment of building indoor environments will play an increasing role. In defining scientific questions, it is necessary to observe how real buildings and real occupants function, and learn from that. The following is an example of how assessing the thermal environment in actual operating buildings was able to lead to new understanding with great energy conserving potential.

II. LEARNING FROM OCCUPIED BUILDINGS

In 1985 a set of studies was commissioned by ASHRAE to see whether buildings were actually following the provisions of their thermal comfort standard, and also to see whether the laboratory-study-based thermal comfort zones specified in the standard were correct based on field observations in operating buildings (Schiller et al. 1988).

To accomplish this, it was necessary to tour through a large number of buildings taking detailed physical measurements of the four environmental variables that affect comfort, together with information about the individual occupants' clothing and metabolic rate. From these measurements indices such as Effective Temperature and PMV could be calculated. At the same time, the occupants were surveyed for their sense of thermal sensation and thermal acceptability. This allowed direct comparison between the indices and the comfort-related responses of the occupants.

The study was repeated in four climate zones, and ASHRAE subsequently funded another grant to assemble the data from these and similar studies done worldwide into a public database (de Dear 1998). This database allowed an earlier hypothesis of Humphreys (1978) to be tested further, concerning differences between the comfort requirements of occupants in buildings with natural ventilation versus those in buildings with central air conditioning (de Dear and Brager, 2001).

Centrally-controlled HVAC buildings Naturally ventilated buildings

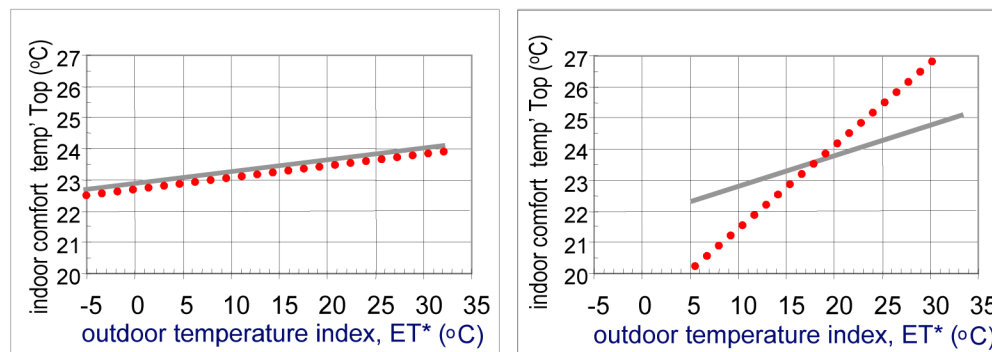


Figure 1. Indoor neutral comfort temperature in HVAC and naturally ventilated buildings.

— Predicted: Lab-based PMV model
 Observed: Field-based adaptive model

Figure 1 shows that for people in naturally-ventilated buildings, the monthly mean outdoor temperature changes their interior neutral comfort temperature. There are a number of causes, involving personal expectations and adaptations triggered by their ability to control their own environment by way of the windows, and closer experience with the outdoor climate. The energy conservation potential of the naturally ventilated curve is very great. The Adaptive Comfort Model, that predicts this effect, is now part of ANSI/ASHRAE Standard 55 (2004) for buildings where the occupants have control over operable windows.

III. REASONS FOR ASSESSING INDOOR ENVIRONMENT

There are many types of building environment assessment. The following table lists people who may use them, and for what purposes.

Researchers	Developing indoor environmental standards, and design guidance
Designers	Obtaining feedback about designs and use of technology
Building owners	Evaluating quality of buildings and their maintenance staff
Building operators	Operating setpoints; diagnosing causes of failures and complaints
Commissioning agents	Obtaining feedback during HVAC system calibration
Employers	Maintaining employees' satisfaction and productivity
Occupants	Managing their environmental control costs

This paper describes assessment techniques that we have been using at Berkeley to address each of these functions. It also describes several research results that were derived from such assessments, each of which having energy conservation implications. In general, our focus is on comfort and energy, rather than on air quality and health.

IV. ASSESSMENT TECHNIQUES

We are using the following types of assessment techniques: the first three obtain physical measurements, and the last three involve surveying occupant perceptions and opinions.

Number 4 involves both.

1. Mobile instrumented carts for research on comfort requirements, on performance of new technologies, and for appraising individual building performance.
2. Fixed indoor climate stations for workstation monitoring over time.
3. An instrumented cart connected with a wireless sensor array for commissioning buildings.
4. Wireless sensor/actuator arrays for residential energy/environmental control.
5. 'Right-now' surveys (via laptop and web)
6. Automated comfort polling stations
7. Web-based occupant satisfaction survey

1. THERMAL COMFORT CARTS

Both the ASHRAE and ISO comfort standards measure the seated comfort zone at three levels: 0.1, 0.6, and 1.1 m, with the additional level 1.7m for standing. To speed up the determination of how well particular indoor environments meet standards, it helps to measure these three heights at the same time and automate the data collection. Figure 2a and 2b show our initial cart for the first ASHRAE building study, and Figure 2c shows the more collapsible cart used in the subsequent studies. The measurement procedure began by surveying individual occupants at their workstation, using a laptop computer. As soon as this was finished, they would be asked to take a break and the cart would replace their chair for 5 minutes as measurements were taken. The carts incorporate a chair seat and back to provide the directional shielding from radiation and draft that an occupant would experience. The

instrumentation is laboratory grade, including air temperature, omnidirectional velocity, globe temperature, humidity, plane radiant temperature asymmetry, and light.



Figure 2a,b,c. Carts used in building field studies

2. FIXED WORKSTATION MONITORS

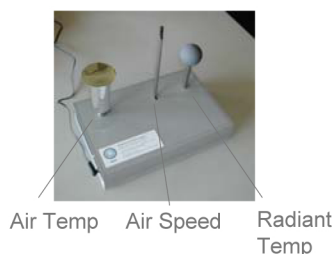
Similar instrumentation can be stationed on a worker's desktop over time to record a detailed record of the workstation climate. Termed indoor climate monitors (ICMs), they are similar to Fishman and Pimbert's sensor unit (1979) but include air velocity as well. The units have shielded air temperature, humidity, a rugged hooded anemometer with properties close to omnidirectional, globe temperature, and (by splitting the globe on newer models) plane radiant asymmetry. The units must be inexpensive because one tends to need a large number of them, and they are usually left in the office for long periods. We often extend the area covered using conventional temperature loggers.

Data is recorded on an internal datalogger. We recently developed a mesh-networked wireless prototype that allows real-time remote monitoring—this is a major improvement.

The ICMs have been used in short-term to season-long studies. Each test subject receives a unit, and is prompted a few times each day to respond to a short comfort survey on the internet. These instruments were the source of physical data in the air movement acceptability study described at the end of this paper.



Figure 3. Indoor climate monitors and their uses in field studies.



Field studies tend to require large numbers of ICMs

3. BUILDING COMMISSIONING CART

A major corporate headquarters tower in New York has underfloor air distribution (UFAD). Because UFAD is a new technology in the US, a measurement cart was developed to organize the initial commissioning of the system. The cart will subsequently be used to monitor the building performance over time as part of ‘continuous commissioning’, a rare but desirable practice.

UFAD requires maintaining an appropriate vertical temperature profile in the room by controlling air supply rate and temperature entering the room. These vary across the large floor plate due to the way supply air travels in the plenum.

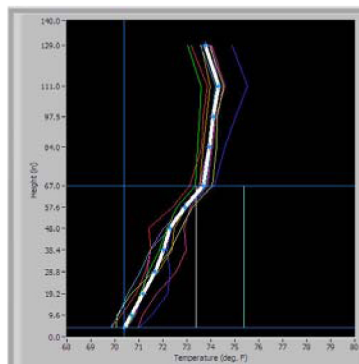
The cart itself has a telescoping thermocouple array that measures temperature profiles with rapid response time. Infrared sensors measure floor and ceiling temperatures, and supply air plenum pressures are measured. The cart carries a laptop computer that serves to acquire data, analyze data, and serve as the operator’s graphic user interface.

In addition, the cart acquires data from an array of 70 wireless sensors that measures supply air temperatures in floor-mounted diffusers, updating every few seconds through a mesh network using the TinyOS operating system. The mesh network communicates to a base station positioned somewhere mid-array, and this station communicates with the cart through WiFi. The cart data is also uploaded to our Berkeley database via the internet (Figure 5).

Detailed commissioning procedures and pass/fail criteria are contained in the cart software, letting the operator immediately know whether the commissioning was successful. Three operating modes have emerged in this project: ‘walk-through’ for spotting blatant flaws, tests with artificial heat loads, and measurements over various time lengths under actual occupancy.



Figure 4a Commissioning cart with extended mast



4b Screen shot of air temperature stratification measurements



4c Screen shot of supply air temperatures (round) and mid-level room temperatures (squares)

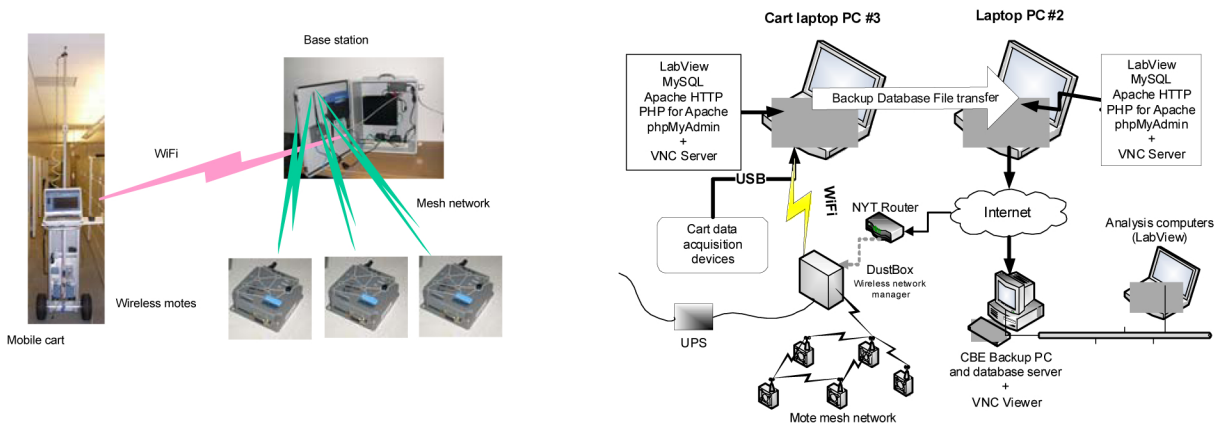


Figure 5. Wireless network connections

This type of commissioning cart has general applicability in assessing buildings, in that it can quickly and continuously obtain simultaneous environmental conditions over large indoor areas. Its ability to transmit data in real time to remote observation locations will make it useful for both experiments and for building operators.

4. WIRELESS ARRAY FOR DISAGGREGATED RESIDENTIAL THERMOSTAT

We have used wireless mesh networks in another project to develop a home energy control system based on standalone sensors and actuators (Arens et al. 2006). It monitors many environmental and energy sensors in the house, and also obtains broadcasts of supply-sensitive electricity prices from the utility. From these it is able to make control decisions for air conditioning, fans, and electricity-consuming appliances. It was developed to encourage residential demand response, but could be generally used for energy conservation.

The system assesses *climate*, *occupancy*, *energy use* and *energy cost*, and provides interpreted information to the occupant. For example, it suggests turning off equipment during periods of shortage and high electricity price, and allows the occupant to decide the tradeoffs between cost and comfort that they wish at any given time. It is designed to automatically learn both the building's thermal properties and the occupants' thermal behavior and preferences. In its interactions with both the building and the occupant, it might be considered a form of 'ambient intelligence' (Arens et al. 2003).

5. RIGHT-NOW SURVEYS

In thermal comfort experiments, one must obtain occupants' subjective responses along with coincident physical measurements of the environment. In the 1980's and 90's the thermal comfort physical carts were accompanied with a 'right-now' survey of thermal sensations and acceptability ratings administered on a laptop. Now questions for office workers are usually presented over the Web. The form of these questions has evolved over time, and we use several forms. It is desirable (for temperature in this case) to present at least three questions covering sensation, acceptability, and preference:

Figure 6 shows a scale used in tests of control strategies to improve ‘demand response’. Since electrical demand is greatest during the afternoon hours of hot summer days, we are interested in how much one can practically precool a building in the morning and subsequently turn off the air-conditioner and let the temperature float?. The web screen presents the ASHRAE seven-point thermal sensation scale, a choice of whether this is acceptable or not, and a question about whether the occupant would prefer to be warmer, cooler, or no change.

Figure 6. ‘Right now’ web-based survey

6. COMFORT POLLING STATIONS

In buildings with transient occupancy or where employees do not have access to a computer, occupant reactions can be surveyed through an automated polling station. The type shown in Figure 7 has been used in demand-response precooling studies in stores, banks, and a museum. The building managers’ question was how might their customers be affected by temperature manipulation during demand response events? One can distinguish customers having short versus long exposures within the store by contrasting results from units near the entrance with those at the checkout counter. The polling station has colored diodes that flash to attract attention to the device and then assist the users as they make their selections by pressing buttons. A time delay imposed between entries discourages multiple entries by children, etc. An internal datalogger records both the votes and the unit temperature. The survey scale is a modified Bedford scale, judging both thermal sensation and acceptability.



Figure 7a. Comfort polling station



7b. Station positioned in a bank

So far, we have found that store employees are more affected than the customers. This presents an opportunity in that there may be efficient ways to maintain employees' comfort through localized or intermittent conditioning. In addition, by simply notifying employees in advance that a demand-response event is expected, they bring appropriate clothing and are less affected by the temperature fluctuation.

7. CBE OCCUPANT SATISFACTION SURVEY

For measuring *building* acceptability, as opposed to the acceptability of a given environmental condition, longer-term measurements are needed. For the past 8 years, the Center for the Built Environment (CBE) at Berkeley has been conducting web-based indoor environmental quality surveys in office buildings. The anonymous, invite-style survey measures occupant satisfaction and self-reported productivity with respect to nine environmental categories: office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, cleaning and maintenance, overall satisfaction with building and with workspace (Zagreus et al. 2004). The questions asked in the survey have remained consistent over time to create a standardized searchable database for benchmarking and analysis. At this time the general survey results cover: 320+ buildings, 47,000+ respondents, and 3.8million data points.

The survey was originally developed for a building controls company as a way of proving the quality of their building maintenance service to their customers. But the survey has proved useful for assessing many other things. It is used for evaluating the success of new building technologies, building designs and furnishings, the quality of building operation, as well as for diagnosing problems. Reports are generated automatically for the clients, and they have access to search and filtering tools that allow them to compare their building against others in many ways. An important feature of the survey is its branching questions. If an occupant is satisfied with one of the nine environmental categories, the survey moves to the next category. However, a dissatisfied vote moves to a detailed questionnaire aimed at finding the source of the dissatisfaction. This has proved useful in research on many aspects of building performance.

V. EXAMPLE RESEARCH APPLICATIONS:

1. INDOOR ENVIRONMENTS AS PERCEIVED BY OCCUPANTS

Figure 8 presents the average building scores for each category in the survey across the entire CBE database. People in general rate their buildings favorably. However, acoustics and thermal comfort have negative scores, and air quality is the third lowest.

The thermal comfort and air quality categories are analyzed below.

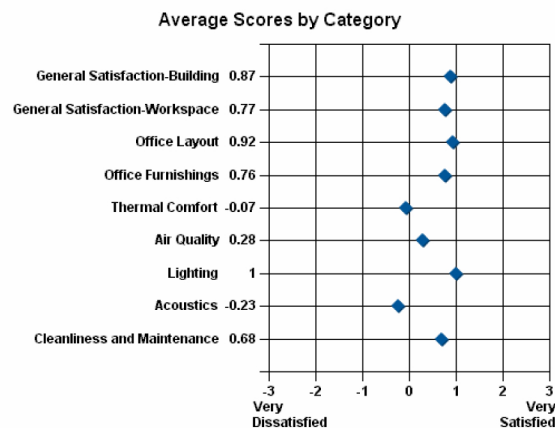


Figure 8

Thermal Comfort

Figure 9 shows the distribution of thermal comfort satisfaction scores for all occupants. Overall, more occupants are dissatisfied (42%) than satisfied (39%), with 19% neutral. Note the relatively high percentage of responses in the -2 and -3 categories (27%).

One can also look at the proportion of occupants satisfied with temperature in each building, and plot these in a frequency distribution (Figure 10). We see that in just 11% of the buildings, 80% or more are satisfied with temperature in the workspace.

With respect to thermal comfort goal set out by standards, many buildings appear to be falling far short. ISO Standard 7730:1994 recommends acceptable conditions in which at least 90% of people are satisfied with their thermal environment. ASHRAE Standard 55-2004 defines the same limit but recognizes that local discomfort and asymmetries could produce an additional 10% dissatisfaction, for a total of 80%. The survey results shown in Figures 9 and 10 clearly indicate much higher rates of thermal dissatisfaction in buildings.

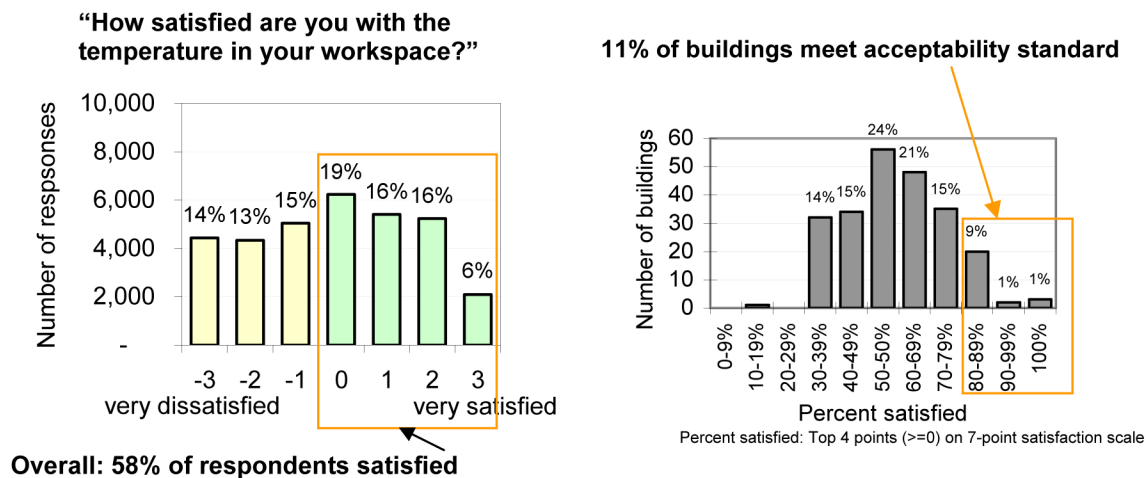


Figure 9. Distribution of thermal comfort satisfaction among occupants

Figure 10. Distribution of buildings by percentage of occupants satisfied with thermal comfort (top 4 points, ≥ 0 , on the 7-point scale)

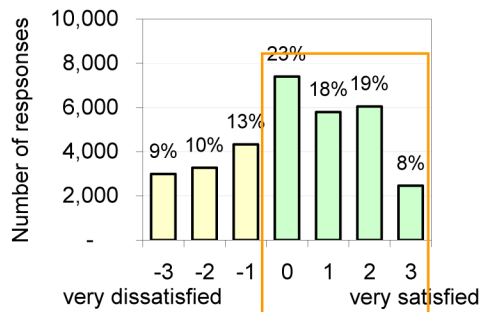
This raises interesting questions about how to assess satisfaction/dissatisfaction. The ASHRAE/ISO recommended percentages relate to 'right-now' evaluations of point-in-time environmental conditions. In contrast, the CBE survey directly asks the occupant's satisfaction with the thermal conditions in the workplace. We might expect a larger percentage of dissatisfied responses in the CBE survey, because occupants have not forgotten uncomfortable episodes from the past when they evaluate a building space. Their recollections tend to encompass several months.

Air Quality

Air quality satisfaction is higher than thermal satisfaction in the survey database. Figure 11 shows the distribution of air quality satisfaction votes across all occupants. In contrast to the thermal satisfaction votes, more occupants voted >0 (45%) than <0 (32%), and the average vote was positive (0.17).

ASHRAE Standard 62.1-2004 defines acceptable air quality as conditions in which more than 80% of people do not express dissatisfaction. In our database 26% of buildings meet the intent

of this standard. Figure 12 shows the distribution of buildings arranged by the percentage of occupants in them who have voted ≥ 0 on air quality satisfaction. The average building satisfaction rate is 68%. As with thermal comfort, there are interesting issues about how such results should be interpreted. Should the standards' recommended acceptability values represent the occupants' longer-term view?



Overall: 68% of respondents satisfied

Figure 11. Air quality satisfaction distribution

26% of buildings meet acceptability standard

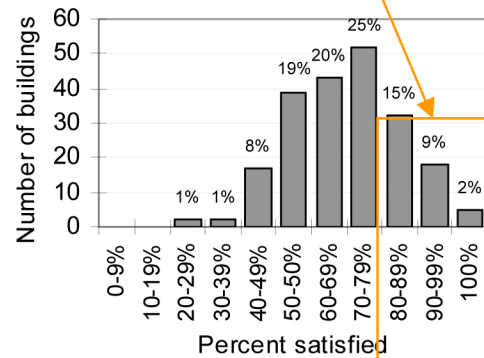


Figure 12. Air quality distribution of buildings meeting satisfaction criteria (satisfaction: top 4 points, ≥ 0 , on the 7-points scale)

2. AIR MOVEMENT PREFERENCES

The limit on air movement imposed by ASHRAE Standard 55 is restrictive in neutral- to warm conditions. The limit varies somewhat depending on the air temperature and turbulence intensity, but is barely above what most people can perceive. For example, at 77°F (25°C) the maximum velocity allowed by the standard is 46 fpm (0.23 m/s). Typical occupied zone air velocities from ceiling fans are in the range of 100-200 fpm (0.5 – 1.0 m/s), so according to Standard 55 these air velocities would be far too high. In cases where the occupant has direct control over air motion, the standard allows air motion to be as high as 160 fpm (0.8 m/s), but in many office situations individual control of air motion is difficult to accomplish.

Providing air movement indoors is typically much more energy-efficient than additional air conditioning. It is very important to know whether such an energy-efficient practice could be acceptable, or equivalent, or even superior to air conditioning.

The Berkeley Civic Center is a naturally ventilated building without air conditioning and with roughly half the office workers having access to an operable window. Brager (2004) in a study of operable windows, took desktop climate measurements with ICMs, and administered right-now and background surveys over summer and winter seasons.

Examining their results (Zhang et al. 2006) found that in neutral to warm conditions, about half the building's population wanted more air movement and only 4% wanted less. Even when measured air velocities were above 0.2 m/s (40 fpm), occupants that wanted more air motion outnumbered those who wanted less by more than 10 to 1 (Figure 13). Preference for "less air motion" exceeded that for "more" only at thermal sensations of -2 (cool) or colder (Figure 14). Providing air motion above 0.2 m/s (40 fpm) was equivalent to lowering the air temperature by 1°C.

Figure 13. Air movement preference for those high-air-motion cases that were judged 'unacceptable' (measured air velocity > 0.2 m/s)

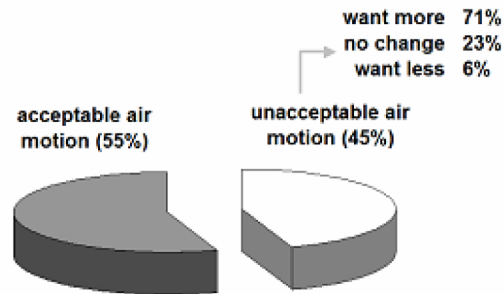
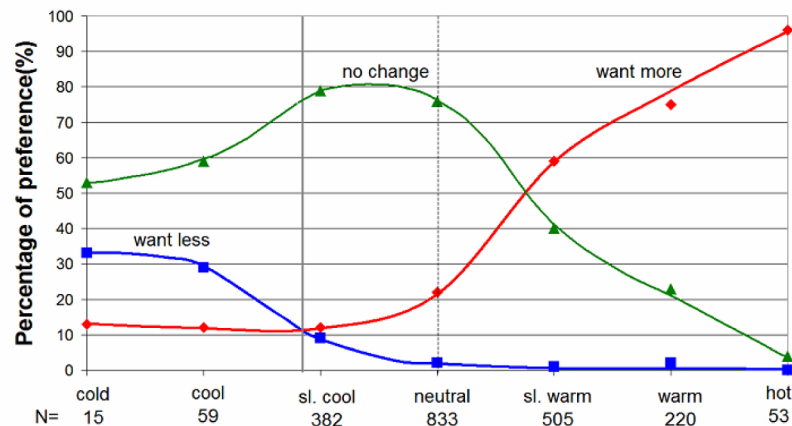


Figure 14. Air movement preference and thermal sensation for "right now" survey



These results are supported by the overall CBE survey database of over 300 buildings of all types. There are more than twice as many occupants indicating that the air motion is too low in their workspace as there are indicating that air motion is too high. If we consider only those responses from occupants who indicate that their space is often too hot, five times as many occupants say the air motion is too low.

These findings are consistent with those of a recent study by Toftum (2004) who examined air movement in the ASHRAE thermal comfort database (de Dear 1998).

In conclusion, these results from field assessments raise questions about the ASHRAE and ISO draft limits, especially under neutral and warm conditions. They suggest the draft limit in ASHRAE Standard 55 should only apply when people feel cool.

3. PERCEIVED AIR QUALITY RELATED TO THERMAL COMFORT AND AIR MOVEMENT.

The satisfaction with *air quality* was relatively high in the Civic Center study, compared with the entire CBE database of buildings. For the entire database, the average satisfaction is 0.27 on the scale: -3 (dissatisfied), 0 (neutral), +3 (satisfied). For the Civic Center, it was 0.72 in the cool season and 1.12 in warm season, ranking in the 65th and 81st percentiles of the whole database (Figure 15). The indoor operative temperature in the summer was 24.2°C, 1.4K warmer than the winter value (22.8°C), and the thermal sensation was also slightly warmer in summer (0.4) than in winter (0.1).

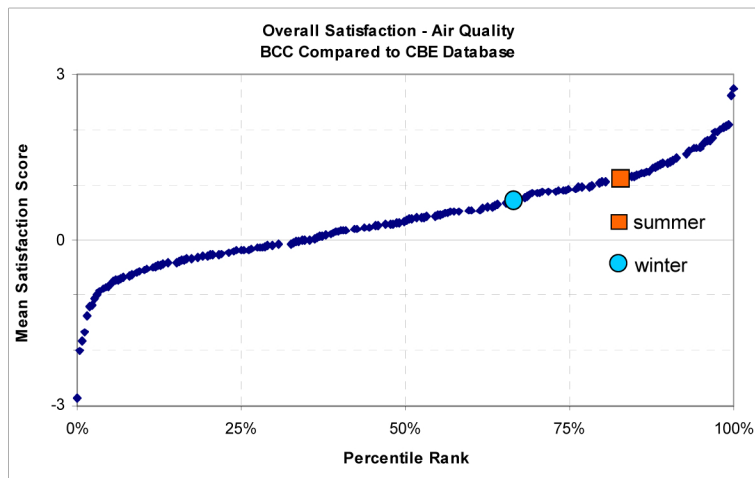


Figure 15. The ranked percentiles of perceived air quality (summer and winter) in the Civic Center compared with the whole CBE IEQ database

It is interesting that the perceived air quality was more satisfactory in the summer, warmer both in terms of air temperature and in the occupants' thermal sensation. It contrasts with Fang et al.'s (1998) finding that perceived air quality is better in cool environments than in warm environments. This might be caused by ventilation rate, but the building is well ventilated in both seasons. It might on the other hand be caused by the higher air movement in summer (average 0.09 m/s, maximum 0.95 m/s) than in winter (0.04 m/s, maximum 0.75 m/s). Here are three possibilities:

The higher air movement might be disrupting the thermal plume around an occupant's body, which normally transports pollutants from carpet and body surface up to the breathing zone, and thereby improve the occupant's perceived air quality. Alternatively, experience with ventilation and outdoor breezes might cause people to associate perceived air movement with better air quality. Finally, Humphreys et al. (2002) found that perceived air quality is affected mostly by thermal sensation. The perceived air quality at neutral sensation was higher than at other thermal sensations, especially the warm sensation categories. So air movement in warm environments might be enhancing perceived air quality by increasing bodily heat loss and therefore comfort. This does not fully explain how the summer perceptions were superior (since the people felt warmer), but could be a factor. In any of these cases, it may be counterproductive to associate perceived air quality with temperature alone, without considering such potential effects of air movement.

VI. EXTENDING ENVIRONMENTAL ASSESSMENT IN THE FUTURE

Research: as suggested by the above examples, we must re-examine each energy-consuming aspect of conventional building operation; contrasting field observations of performance with knowledge drawn from laboratory experiments. It is important to draw boundaries around scientific problems in the right places, and we should expect these boundaries to be redefined in the future. For example, what is the role of personal control: should the Adaptive Model apply to task-ambient conditioning systems as well as windows?

Design: ‘green’ and ‘sustainable’ design needs to be thoroughly assessed as it evolves. In our survey so far, green buildings are superior to conventional buildings in perceived air quality and significantly worse in acoustics (Abbaszadeh 2006). There are reasons for the latter that can be identified and worked on. Designers should routinely survey their buildings’ occupants and learn from them; a requirement for this has just become part of green certification in the U.S.

Building operation: occupants, operators, and owners will all benefit from increased assessment of building’s physical conditions, energy costs, and occupant wishes. Fortunately the Web and wireless advances make this technically and economically possible. System performance should be diagnosed during initial commissioning and be continuously monitored thereafter. For the most promising building types (mixed-mode and hybrid designs) the occupants must become more involved in (or aware of) building operation to assure that it works properly and that they do not act in a way that sabotages it. David Wyon’s formulation of *Three I’s* should become pervasive: assessment devices should provide both *Information* and *Insight*, and design and technology should provide the occupant *Influence*. In the future, we should expect a combination of sensors, actuators, and occupants to work together to improve both the efficiency and the quality of the indoor environment.

Whether these improvements will be sufficient to reverse the increasing damage to the global environment is unclear, but we do know we must do our best to make them happen.

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