4695 (RP-1161)

Operable Windows, Personal Control, and Occupant Comfort

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ABSTRACT

Past research (ASHRAE RP-884) demonstrated that occupants of naturally ventilated buildings are comfortable in a wider range of temperatures than occupants of buildings with centrally controlled HVAC systems. However, the exact influence of personal control in explaining these differences could only be hypothesized because of the limits of the existing field study data that formed the basis of that research. The objective of ASHRAE RP-1161 was to quantitatively investigate how personal control of operable windows in office settings influences local thermal conditions and occupant comfort. We conducted a field study in a naturally ventilated building where occupants had varying degrees of control over the windows. Utilizing continuous measurement of each subject's workstation microclimate, plus a Web-based survey that subjects took several times a day and was cross-linked to concurrent physical assessments of workstation microclimatic conditions, we collected over 1000 survey responses in each of the two main seasons. The data show that occupants with different degrees of personal control had significantly diverse thermal responses, even when they experienced the same thermal environments and clothing and activity levels. Our findings offer further empirical support for the role of shifting expectations in the adaptive model of thermal comfort.

INTRODUCTION

Thermal environments in buildings with operable windows are typically more variable than conditions found in fully air-conditioned buildings, but research studies have demonstrated that they are not necessarily less comfortable. In particular, ASHRAE RP-884 (de Dear and Brager 1998) developed and analyzed a worldwide database from thermal comfort field experiments conducted in buildings that were either naturally ventilated (i.e., occupant-controlled operable windows) or had centrally controlled HVAC systems (in which occupants had no control over their environment, similar to the laboratory studies). One of their primary findings was that occupants in the naturally ventilated buildings accepted, and actually preferred, a significantly wider range of temperatures compared to occupants of the HVAC buildings. Furthermore, these comfortable indoor temperatures were noted to follow the seasonal shifts in outdoor climate and often fell beyond the ASHRAE Standard 55-1992 (ASHRAE 1992) comfort zones. These differences could not be entirely accounted for by conventional thermal comfort theory and the factors that affect a body's heat balance (i.e., dry-bulb temperature, mean radiant temperature, air speed, humidity, clothing insulation, and metabolic rate). One of the hypotheses advanced for this anomaly was that naturally ventilated buildings afford their occupants greater degrees of thermal control than air-conditioned buildings, and that this sense of control leads to a relaxation of expectations and greater tolerance of temperature excursions. Environmental psychologists have long known that human reaction to sensory stimulus is modified when a person has control over that stimulus (Brager and de Dear 1998). A related explanation is that people are more accepting of variations that come from a known source having predictable behavior (Bordass et al. 1994), which is often the case in a naturally ventilated building.

A greater understanding of the influence of personal control has implications for building design, occupant comfort, and energy use. If people remain comfortable in a wider range of conditions in naturally ventilated buildings that provide personal control, significant energy can be saved by

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relaxing thermal comfort standards and allowing more variable indoor temperatures that cycle or drift in response to the natural swings of the outdoor and indoor climate (Milne 1995; Baker and Standeven1996). While the standards do provide some allowances for varying thermal conditions, the limits are fairly limited and are again based on laboratory studies in which subjects were given minimal or no control over the conditions they were experiencing. These laboratory studies may not necessarily be directly transferable to real buildings.

When thinking about naturally ventilated buildings, probably the most important architectural issue is the window. Windows can be used for ventilative cooling of the building structure and, more importantly for this paper, the attainment of thermal comfort by moving air through the building. However, our understanding of the effect of air movement on occupant comfort in real buildings is limited. The draft limits in ASHRAE Standard 55 are very low, and a literature review by Fountain and Arens (1994) explored a number of studies that indicate that personally controlled air movement is an underutilized cooling method in contemporary design.

Specific knowledge about the influence of operable windows and the personal environmental control they afford on indoor thermal conditions and occupant comfort will give designers much needed information on how to design naturally ventilated buildings. ASHRAE RP-884 began this process by developing an adaptive model of comfort that was incorporated into the revised ASHRAE Standard 55 (ASHRAE 2004) as an alternative compliance method for naturally ventilated buildings. However, the research was not able to disentangle the precise effect of personal control from all the other potential explanations for people's acceptance of more variable thermal conditions for two important reasons. First, the empirical basis of ASHRAE's adaptive model project, namely, data from past field studies, was mostly based on traditional, single-point-in-time thermal comfort measurements. As such, we don't know anything about the thermal conditions people had been exposed to prior to the conditions that were measured and assessed by questionnaire. Secondly, past field studies in naturally ventilated buildings did not typically ask detailed questions about whether or not each of the subjects actually had the ability to personally control a window, nor how they used that control or perceived its thermal comfort effectiveness. Without that information, we cannot make a direct connection between the effects of personal control and thermal perceptions.

Toward these ends, the objective of this project was to design and carry out a field study to quantitatively investigate how personal control of operable windows in office settings influences local thermal conditions and occupant thermal comfort, particularly the acceptability of thermal variability.

Figure 1 *Berkeley Civic Center, west facade.*

METHODS

Description of Building

Following an extensive search, we selected the Berkeley Civic Center (BCC), located in the San Francisco Bay area, as the building meeting the greatest number of our selection criteria. The five-story, 77,000 ft^2, U-shaped building (shown in Figure 1) houses city government and administrative offices. There are approximately 230 people working in the building. It is predominately open plan (approximately 80% of the offices), two workstations deep from the perimeter, with a regular layout and access to windows. There are also private offices primarily in the corners of the building. This is a purely naturally ventilated building (i.e., no air-conditioning) with varied cooling strategies that include cross-ventilation through operable windows, stack ventilation through dedicated ventilation stacks, ceiling fans, and exposed thermal mass. The building perimeter has manually controlled radiators for heating but is mostly passive in its cooling mode except for centrally controlled inlet and outlet vents on the ventilation shafts and fan-driven stack assist when needed. The physical layout presented the opportunity to survey occupants with varying levels of direct or indirect personal control based on their proximity to the operable windows. Subjects on the perimeter (open plan and private offices) have direct access to at least three operable windows—two casements and one hopper. Subjects in the core zones are usually one desk away from the window, are most likely directly affected by it, but have less control over its operation. Most subjects in the core have easy access to windows but must interact with people on the perimeter to use the windows.

Table 1.   Field Experimental Methodology

	Background Study	**Detailed Study**
Physical Measurements	Continuous ambient indoor conditions: temperature and humidity in different zones within the building	Continuous desktop indoor conditions: dry-bulb temperature, globe temperature, air velocity, plus nearby meteorological station
Web-Based Survey	Background Survey: one time, seasonal impressions, 10-15 min. long	Repetitive Survey: several times/day, current impressions, 1-2 min. long
Subject Pool	Administer survey to entire building occupant population	Administer survey and monitor workstation microclimate for 38 subjects
Duration and Frequency	2-week period in each of 2 seasons (warm & cool); subjects took the survey only once, at their convenience, during that period.	2-week period in each of 2 seasons, immediately following the Background Study; subjects took the survey repetitively during that period, on average 2-3 times per day

Experimental Methodology

Our methodology included automation of physical (workstation microclimatic) and subjective (questionnaire) data over different time scales and building occupant groups, plus data collected by objective observations of the workstation and exterior facade characteristics of the building as they relate to our research questions. Table 1 shows the two complementary levels of investigation.

Additional documentation during the detailed study included façade photographs of operable window and blind position (warm season only) and sketches of workstations showing researchers' observations about availability and use of adaptive mechanisms. All procedures were reviewed and approved by UC Berkeley's Committee for the Protection of Human Subjects (CPHS) to ensure that subjects knew their participation was voluntary and their identities and individual responses would be confidential, and that researchers would obtain informed consent and minimize risks and disruption to the participants. In addition, we consulted with CPHS and others to ensure that our procedures minimized any bias in our data.

Physical Microclimatic Measurements

A combination of commercially available equipment was assembled to allow close-to-laboratory-grade continuous monitoring of 38 subjects. We collected both continuous desktop and ambient measurements to allow us to sufficiently characterize the spatial and temporal variability experienced by the subjects and calculate PMV as a comparative index. Indoor physical measurements were made at each workstation with a custom designed and fabricated instrument, the Indoor Comfort Monitor (ICM), that was placed on each subject's desk, as near to them as possible without unnecessary exposure to heat sources. The ICMs are designed to collect continuous measurements of dry-bulb temperature, globe temperature, and air velocity (from which *MRT* could be derived using the equation in chapter 14 of the *ASHRAE Handbook—Fundamentals* (ASHRAE 2001). The ICM is housed in a 2 in. × 6 in. × 8 in. electronic enclosure with three stainless

steel tubes supporting the three sensors. The ICM "globe" thermometer (diameter 1.6 in.) is painted matte grey to become a radiation absorber, or radiant temperature sensor, mimicking the human body's emissivity of $\varepsilon \approx 0.95$. In contrast, the dry-bulb temperature sensor is shielded from radiation by a highly reflective aluminized film, but it is subject to free-flowing ventilation through the large openings at the top and bottom. In the center of the ICM is the heated thermistor anemometer. The commercially available glass bead thermistor anemometers adopted in this study have a 0.01 m/s resolution, are factory calibrated to NIST standards, and do not have a strong directional bias compared to other low-cost anemometers that fit within our research budget. After testing the anemometers in our wind tunnel, we determined that they would comply with ASRHAE Standard 55 if we aligned them within 30 degrees of the dominant direction of air movement (in our case, toward the window). As input for our analysis, warm season air speeds were calculated by taking a three-point average of the instantaneous air speed (over 15 minutes). Cool season air speeds were a continuous average of the last five minutes (three-second sample period). A signal conditioner for the anemometer and a data logger are housed inside the ICM's box. After testing the thermistor sensors in a standardized calibration chamber, the ICMs were individually assembled, calibrated, and quality controlled in our laboratory before going out into the field. This device exceeds ASHRAE Standard 55 specifications for ambient temperature and radiant temperature accuracy, while approximating the guideline for air speed. More details about the design of our instrumentation can be found in the final report (Brager et al. 2004).

Humidity was monitored with separate data loggers distributed one per cluster of subjects because of its relatively homogeneous distribution within the occupied zones of our subjects. Meteorological data were obtained from two local stations that meet standardized measurement guidelines and from our own outdoor temperature sensors and weather station on the roof. After analysis, the data from the UC Berkeley Environmental Health and Safety (EH&S) meteorological station (only a few blocks away from BCC) was chosen as the most accurate. The EH&S station is 75 ft

above the top of the building and is regularly checked by the Bay Area Air Quality Management District, and the sensors are calibrated four times/year.

Subjective Measurements

We collected our subjective measurements using a Web-based survey tool developed by the Center for the Built Environment at UC Berkeley (Huizenga et al. 2002). Not only did this facilitate automated collection of data (eliminating keyboard entry errors), it also allowed us to use branching features so that selected follow-up questions are linked to subjects' particular responses. Consistent with our overall experimental plan, we developed two separate but related surveys: (1) the general Background Survey and (2) the short, Repetitive Survey, the data from which were linked by time-and-space coordinates with the instantaneous indoor climatic observations described above. In addition to checklists and scaled responses, both surveys provided frequent opportunities for the subject to insert comments.

The Background Survey was administered to all occupants of the building once during each seasonal study and asked about general impressions related to the typical weather of that season (e.g., "*How satisfied are you with your thermal comfort in your workspace in warm/hot weather?*"). Because Berkeley often gets cool days in the summer and warm days in the winter, we specifically asked the question in terms of "weather" rather than "season." The Background Survey took approximately 10-15 minutes to complete. It included questions about basic demographics, personal workspace characteristics, various personal environmental control opportunities, window operation, and satisfaction with various environmental attributes.

The Repetitive Survey followed a similar Web-based format as the Background Survey but was designed to assess current (point-in-time) impressions so that we could link it to the instantaneous workstation microclimatic data obtained from the ICM and also the concurrent outdoor meteorological data. The survey took approximately one to two minutes to complete, and subjects were asked to take it several times evenly distributed throughout each day after being at their workstation for at least 30 minutes. The survey presented subjects a list of five different descriptions of office tasks and asked to them check the one that best described their primary activity during the last 30 minutes. Subjects also completed a fairly detailed clothing garment checklist. Metabolic rate (MET) and ensemble clothing insulation (CLO), including the insulating value of a typical office chair (0.15), were then calculated from these survey responses, using procedures in ASHRAE Standard 55 (ASHRAE 2004). In addition to the thermal sensation, preference, and acceptability scales traditionally used in thermal comfort research, the survey also included newly developed questions about thermal variability, air movement, window and blind use patterns, other environmental adjustments, and energy level and mental alertness.
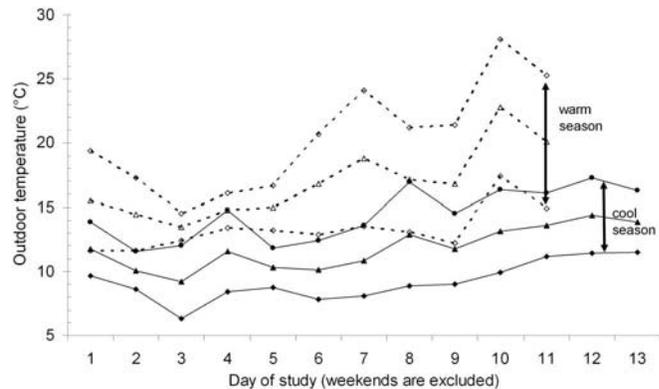

Figure 2 Outdoor temperature during detailed study periods.

Further details about questions in both surveys can be found in the final report (Brager et al. 2004).

Data Processing

The final database required careful quality assurance because it was based on matching and merging time-sequence and background data from four different sources (Background Survey, Repetitive Survey, indoor physical measurements, and outdoor weather data) plus a range of calculated indices. A variety of physical indices were then calculated (some using the *WinComf* software package of Fountain and Huizenga [1996], which was developed under ASHRAE TC 2.1 funding) and merged back into the database. These include mean radiant temperature (chapter 14, *2001 ASHRAE Handbook—Fundamentals*), operative temperature, ET*, SET, PMV, PPD, air speed averages, indoor variability indices associated with each hour (described under "Assessment of Variability"), and outdoor variability indices (daily, weekly, and monthly averages).

RESULTS

There was an extensive amount of data collected in this project, and the final report (Brager et al. 2004) presents a more thorough analysis. This paper focuses on an analysis of the general thermal environment (thermal sensation, preference, and neutralities), assessments of air movement, variability, the influence of personal control, and a comparison to ASHRAE Standard 55.

Berkeley Climatic Context

Figure 2 shows the range of outdoor dry-bulb temperatures during the two two-week Detailed Study periods (weekend data were removed). Our warm season measurements were taken Sept. 24 through Oct. 8, 2002, and our cool season, Feb 26 through March 13, 2003. Min/Mean (diurnal average)/ Max temperatures for these seasons were 11.6/16.9/28.1°C (52.9/62.4/82.6°F) for the warm season and 11.6/11.8/17.3°C (52.9/53.2/63.1°F) for the cool season. We compared our

Table 2. Background and Detailed Study Sample Sizes

	Warm Season (Sept.)	Cool Season (Feb/March)	
Background Study	105	93	(57% repeaters)
Detailed Study - # people	38	38	(22 were repeats)
Detailed Study - # responses	1045	1030	

Table 3. Statistical Summary of Indoor Climatic and Thermal Comfort Indices

	Warm Season				Cool Season			
	Mean	StDev	Min	Max	Mean	StDev	Min	Max
CLO	0.7	0.2	0.5	1.6	0.8	0.2	0.5	1.5
MET	1.3	0.1	1.1	2.1	1.2	0.1	1.1	1.4
DB Temp (°C)	24.2	1.8	19.7	32.9	22.8	1.6	17.5	30.6
MRT (°C)	24.1	1.9	14.9	32.1	23.0	1.6	17.1	34.3
Top. (°C)	24.1	1.7	19.7	32.5	22.9	1.6	17.6	30.6
Air Velocity (m/s)	0.09	0.13	0.00	0.95	0.05	0.07	0.00	0.75
Vapor Pressure (Pa)	1182.9	231.5	654.5	1581.3	1093.4	165.4	855.4	1462.4
ET* (°C)	23.9	1.5	19.7	30.2	22.7	1.5	17.6	29.2
SET (°C)	25.1	1.7	20.4	31.4	24.5	1.8	18.2	26.6
PMV (7-point scale)	0.2	0.5	–1.3	2.2	0.0	0.4	–2.2	1.6
PPD (%)	9.8	7.7	5.0	83.0	9.1	7.7	5.0	83.0
Variability Indices								
Top,StDev (°C)	0.26	0.26	0.02	3.21	0.26	0.26	0.03	2.61
Top,slope (°C/hr)	—	0.8	–6.5	8.1	—	0.9	–4.9	5.9

"*Top,StDev*" and "*Top,slope*" are based on the hour prior to each survey event and represent the standard deviation and slope from a least squares linear regression of the last hour's operative temperature. Mean value of *Top,slope* is omitted since combining positive and negative values is misleading.

measured temperatures to the average min-max range of long-term climate data and confirmed that our selected measurement periods were typical of Berkeley's climate for those times of the year. The trend data for both seasons also revealed other typical characteristics of Berkeley climatic patterns in which the occasional summer fog and sunny winter day produce a familiar pattern of occasional warm daytime temperatures in the winter that are not that dissimilar to some of our cooler foggy days in the summer. Both studies saw a warming trend in the outdoor temperature over the course of the two weeks.

Description of Subjects

The Background Survey was administered to everyone in the building (as opposed to selecting a random sample), and we used a variety of means to publicize the survey and encourage participation. We obtained approximately a 40% to 45% response rate in the two seasons, which is comparable to the range of responses typically achieved with this type of web-based survey (Huizenga et al. 2002). The last question in the Background Survey gave a brief description of the subsequent Detailed Study and asked for volunteers. We coded the volun-

teers by location in the building and office type and selected a short list based on achieving a balance between private and open plan offices, perimeter and core offices (which represented various degrees of access and control of windows), orientation, and obtaining some "clusters" of subjects who would be in proximity to each other but with varying degrees of control. Other than these descriptors, other survey responses were not used as criteria for selection. We obtained a distribution of people in both the Background and Detailed studies that was comparable to the distribution of office types in the building (namely, ca 20% in private offices, 80% in open plan workstations, and of those, about ¾ having some degree of control over a nearby window.) Table 2 summarizes the final sample sizes for each of our studies, after eliminating incomplete data. The 38 participants in the Detailed Study included 24 females and 14 males in each season.

Description of Indoor Climate

Table 3 summarizes the distribution of the indoor climate parameters, calculated CLO and MET levels, and calculated comfort and variability indices during the two Detailed Study periods.

Table 4.   Statistical Summary of Key Survey Questions

Thermal Sensation	Warm Season	Cool Season
mean	0.4	0.1
standard dev.	1.1	1.0
(+3) hot	4%	3%
(+2) warm	13%	11%
(+1) slightly warm	25%	25%
(0) neutral	41%	40%
(–1) slightly cool	14%	19%
(–2) cool	2%	3%
(–3) cold	0%	1%

Thermal Preference	Warm Season	Cool Season
mean	0.3	0.1
standard dev.	0.6	0.6
(1) want cooler	41%	23%
(0) no change	52%	63%
(–1) want warmer	7%	14%

Air Movement Preference	Warm Season	Cool Season
mean	1.6	1.8
standard dev.	0.6	0.5
(1) want more	45%	28%
(2) no change	52%	68%
(3) want less	3%	4%

The data indicate a relatively modest thermal differentiation between the indoor thermal environments in the two seasons, with the mean indoor operative temperature being barely one degree warmer in the warm season, and even the mean indoor air velocities being similar, and in fact low, in both seasons. Indoor humidity was the single largest discriminator between the two seasons, with warm season vapor pressure being over 100 pascals higher than the cool season mean. The variability indices will be discussed later.

Assessment of the General Thermal Environment

Table 4 summarizes the distribution of the key survey questions assessing the general thermal environment. These patterns are discussed further in the following sections.

Thermal Sensation and Preference

Table 4 indicates that thermal sensations were broadly distributed the same way in both warm and cool season surveys, with perhaps slightly more "warm/hot" votes in the warm season and more "slightly cool" votes in the cool season. In both seasons, mean thermal sensation was close to neutral (only slightly higher in the warm season), and 80% to 84% of the subjects are voting within the three central categories of the seven-point scale, indicating that the building was successfully meeting the intent of ASHRAE Standard 55 (i.e., at least 80% of the occupants find the thermal environment acceptable by this criterion).

Despite this broad similarity in thermal sensation distributions, there was a very clear differentiation between seasons in terms of thermal and air movement preferences. Significantly more people want to feel cooler than warmer (even in the winter), although this pattern is stronger in the warm season. Air movement preferences show 45% of subjects in the warm season wanting more air movement, compared to just 28% in the cool season. Only a handful of subjects wanted less air movement than they were actually experiencing in either season, suggesting that draft was not much of an issue

in this naturally ventilated building. Air movement is discussed further below.

Patterns of thermal sensation and preference votes are examined in more detail in Figures 3 and 4, respectively, showing the mean thermal preference votes and coincident distribution for each category of the thermal sensation scale. Figure 3 shows that the acceptability of warm and cool sensations is not symmetric. In the warm season, when feeling slightly warm or cool (±1), subjects' preference to return to neutral is stronger on the warm side than on the cool side. For the more extreme thermal sensations (±2, 3), preference to return toward neutral is fairly symmetric. The cool season shows the same trend. The simultaneous distributions of thermal sensation and preference in Figure 4 reveal a more complex pattern of asymmetry and seasonal differences. Overall, preferred sensations (i.e., average thermal sensation for the group voting a preference of "no change") were near neutral in both seasons. When people are voting a neutral thermal sensation (0), the overwhelming majority (83% to 88%) prefer no change. But when people prefer a sensation other than "neutral," nearly all want to feel cooler in the summer, and they are evenly split in their preferred direction in the winter. Thermal sensations of "slightly cool" seem to be more acceptable than "slightly warm" in both seasons. Of the people feeling "slightly cool," a fairly even 67% to 69% do not want a change in that sensation. Yet when people are feeling "slightly warm," 42% (cool season) and only 23% (warm season) would prefer to stay that way.

Thermal Neutralities

The relationship between thermal sensation and the physical thermal environment was first examined by calculating linear regressions between thermal sensation and various environmental indices (weighted by the number of observations in each environmental index bin). Each regression model uses binned data for the indoor environmental index and the mean thermal sensation in each bin. The R^2
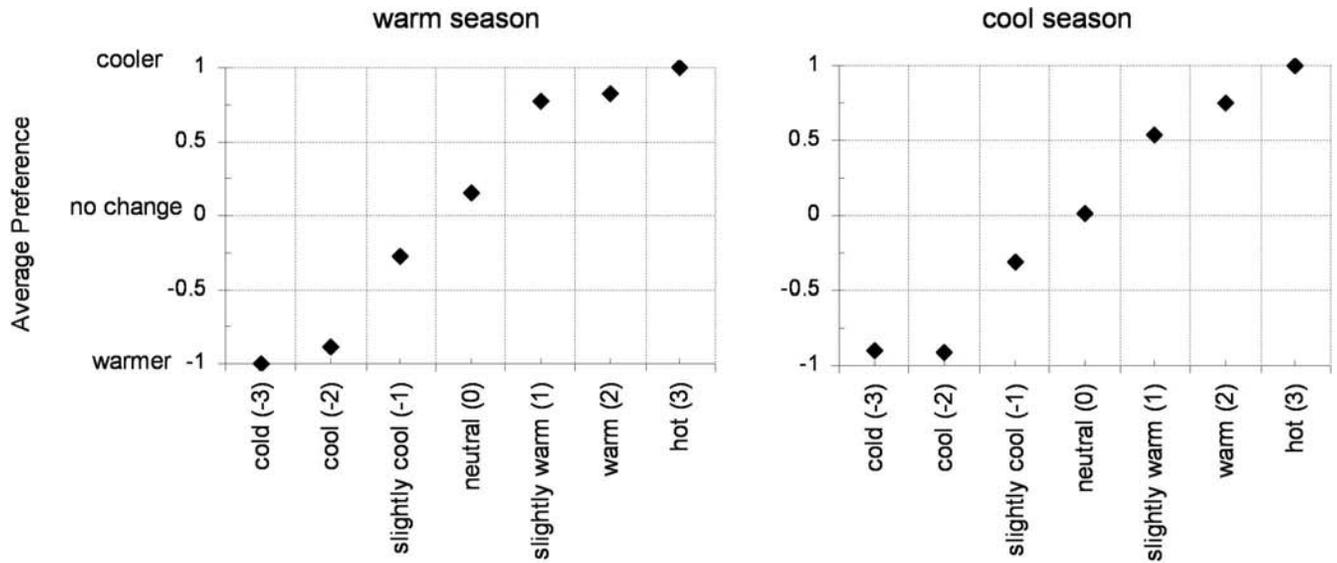
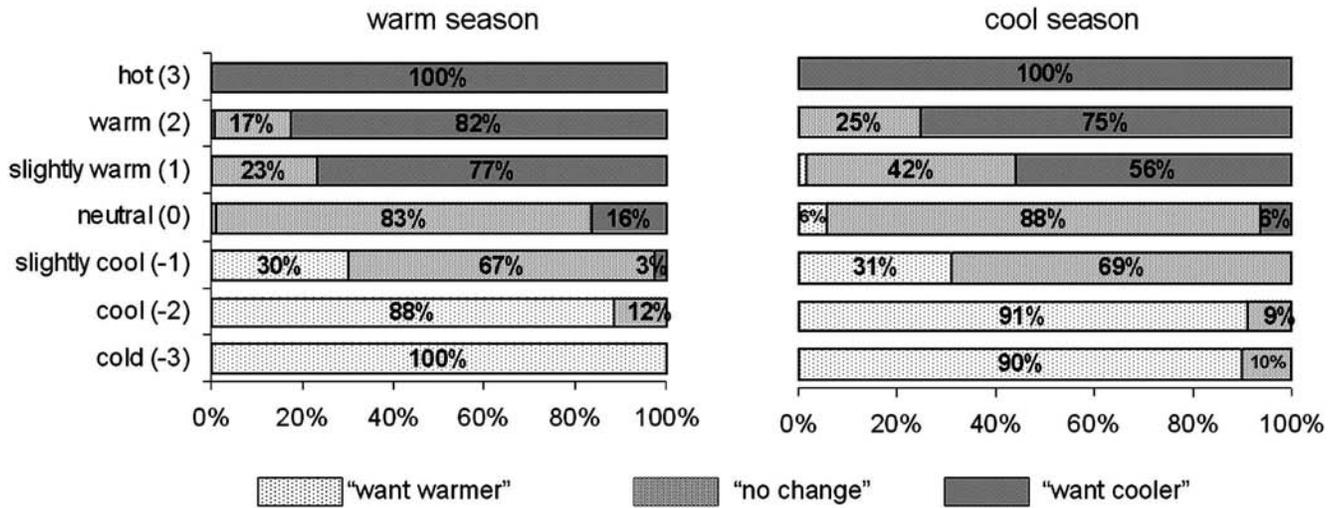**Figure 3** *Average thermal preference vote, coincident with thermal sensation votes.*

Figure 4 *Distribution of coincident thermal preference and thermal sensation votes.*
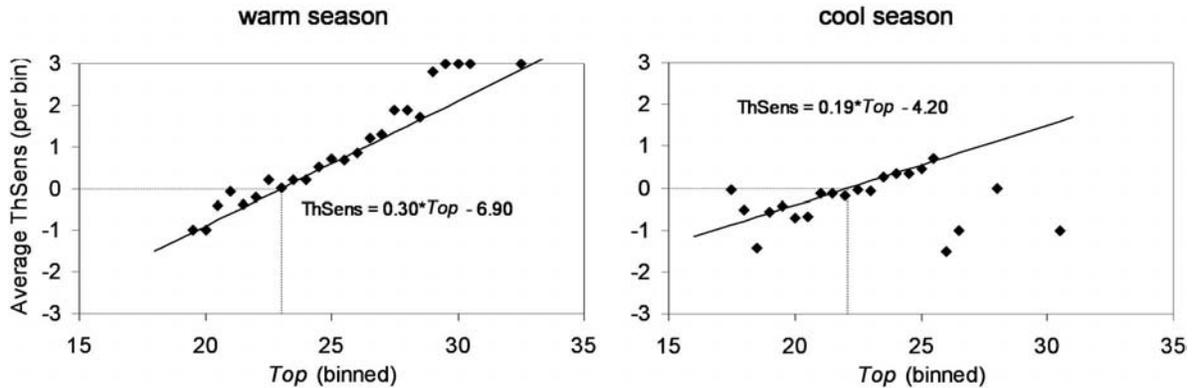
warm season

cool season

Figure 5 *Linear regressions of thermal sensation votes vs. operative temperature (the regression model was weighted by the number of votes falling into each of the temperature bins on the x-axis).*

Table 5.   Regression Model Outputs for Thermal Sensation vs. Different Environmental Indices (°C). All Weighted Regression Models Were Significant at Better Than the 99% Level of Confidence.

		Model	R^2
Warm Season	Top	ThSens = 0.30 *Top* - 6.90	0.90
	ET*	ThSens = 0.34 *ET** - 7.66	0.89
	SET	ThSens = 0.22 *SET* –5.17	0.88
	PMV	ThSens = 0.94 *PMV* + 0.27	0.82
Cool Season	Top	ThSens = 0.19 *Top* – 4.20	0.69
	ET*	ThSens = 0.20 *ET** - 4.44	0.78
	SET	ThSens = 0.10 *SET* - 2.50	0.42
	PMV	ThSens = 0.47 *PMV* - 0.06	0.60

statistic can be interpreted as an index of goodness of fit, with 1.0 corresponding to a perfect linear relationship. The results are shown in Table 5.

In both seasons it appears that thermal sensation votes correlated more strongly with operative (*Top*) and effective temperature (ET*) indices than with the more complex "universal" indices of PMV and SET. Given that *Top* is the independent variable used in both the current and soon-to-be-revised ASHRAE Standard 55, we decided to use *Top* as the basis for all of the subsequent analysis in this paper. The regressions against *Top* are shown in Figure 5. Ideal comfort temperatures are traditionally defined as the neutral operative temperature (i.e., the temperature at which the mean thermal sensation for the group is "neutral"), determined by solving the regression equations for ThSens = 0. In this building, neutral temperatures for the full group of subjects were 23.0°C (73.4°F) (warm season) and 22.1°C (71.8°F) (cool season). In a later section, we examine how neutral temperature varies with the degree of available personal control.

Assessment of Air Movement

The operation of windows in a naturally ventilated build-ing will influence both local temperature and air movement.

The effect of air movement on comfort has primarily been studied in the laboratory, but our continuous monitoring of air velocity at the subjects' desktops provided new opportunities to evaluate this relationship.

Air Speed Distribution and Sensations. Figure 6 shows the distribution of air speed (with the sample size "n" for each bin). Air speeds were low to moderate in this building, with 90% of the measured air speed falling below 0.15 m/s (29.5 fpm) (a typical air speed in an HVAC building). As indicated earlier in Table 3, mean air speed was 0.09 m/s (17.7 fpm) (warm season) and 0.05 m/s (9.8 fpm) (cool season). Unless otherwise indicated, all subsequent air movement analysis in this section was performed with data from both seasons combined (given the few incidences of elevated air speeds, we needed to aggregate the data to allow a statistical comparison). We compared air speed measurements to subjective questions about sensing air movement and found that even at the lowest air speeds of 0.05 m/s (9.8 fpm), 50% of subjects say they sense air movement, rising to 80% of subjects at 0.45 m/s (88.6 fpm). These results are very similar to the laboratory results of Tanabe and Kimura (1994) and Fanger et al. (1998), who both found that 50% of the subjects were able to sense air move-ment at speeds of 0.15 m/s (29.5 fpm). Tanabe and Kimura
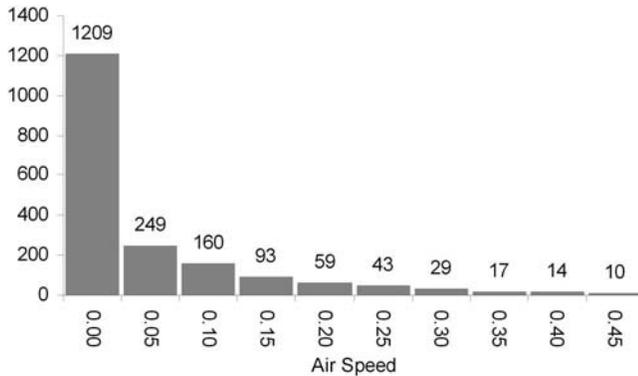
Figure 6 *Air speed distribution.*

Figure 7 *Relationship of mean air movement preference and thermal sensation.*

Figure 8 *Average air velocity and percentage of people wanting more air as a function of operative temperature. Recommended elevated air speeds from ASHRAE Standards 55-1992 and 55-2004 are included for comparison.*

also found that only 10% felt draft at this level, less than what Fanger et al. measured.

Air Movement Preferences and Thermal Sensation. Table 4 showed the responses when people were asked if they would prefer more air movement, no change, or less air movement. Negative sensations of draft were essentially nonexistent in this building (only 3% to 4% wanted less air movement) compared to a significant percentage of people wanting more air movement in both seasons (45% in the warm season, 28% in the cool season). Figure 7 shows the mean air movement preference for each group of people voting a particular thermal sensation on the left and the mean thermal sensation for each group voting for "more," "no change," or "less" air movement on the right. As thermal sensation increased, so did the percentage of people wanting more air movement. Responses were strongly asymmetric, with the overwhelming majority of preference being between "want more air movement" and "want no change." Very few responses called for less air movement, even at the lowest levels of thermal sensation. The right part of Figure 7 shows that the mean thermal sensations that trigger preferences for more or less air movement are symmetric at ±1, and that the group of people who are voting for no change have a mean neutral thermal sensation. This shows that people consciously recognize air movement as having a direct impact on their thermal comfort, and their air movement preferences are for a change of air movement as needed (as necessary) to return to comfort.

Air Movement and Operative Temperature. Preference for air movement was also related to the concurrent temperature and air velocity that people were experiencing. Figure 8 shows that as operative temperature rises, the mean air velocity (read on the right axis) rises slightly, indicating that people are attempting to control air velocity to offset warmer conditions, particularly after approximately *Top* = 24.5°C (76.1°F). Yet the percentage of people wanting *more* air movement rises even more sharply (preference read on the left axis). Also shown are the two lines from the old and new ASHRAE Standard 55, showing the recommended air speed
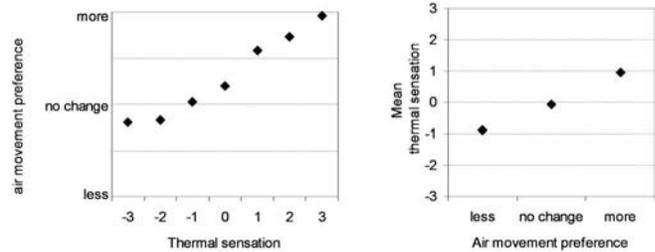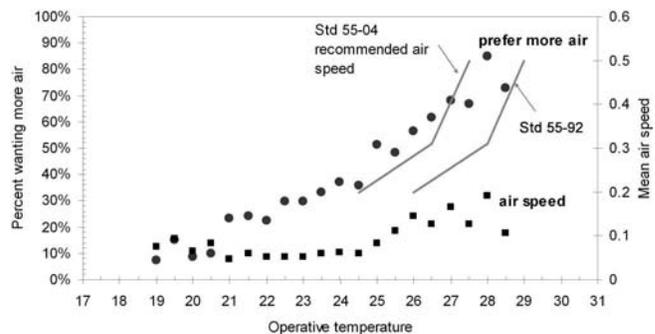
to offset increased temperatures (read on the right axis). The left line is from Standard 55-1992, which says that increased air speed to offset temperature starts at the top of the summer comfort zone, 26°C (78.8°F). The right line is from the newly revised Standard 55-2004, in which the comfort zone is based on PMV and the chart of increased air speed starts at PMV=0.5 (estimated, in our case, to be 1.5°C [2.7°F] above the summer neutral temperature of 23°C [73.4°F]; this results in the line starting at 24.5°C [76.1°F] instead of 26°C [78.8°F]). In both cases we see that the air speeds people were experiencing were much less than the recommended air speed to offset the rise in temperature, which partly explains the finding that increased numbers of people are wanting even more air movement than is being provided. Although 80% of the subjects in the warm season were voting in the "comfortable" categories of the thermal sensation, the 17% who were voting +2 and +3 were not obtaining high enough levels of air movement from the windows and/or ceiling fans to offset the warmer temperatures. But the desire for more air movement is not entirely explained by the need for cooling. Figure 5 shows that the average sensation at an operative temperature of 26°C (78.8°F) was less than +1 (slightly warm) in both seasons, but Figure 8 shows that over 50% of the subjects would prefer
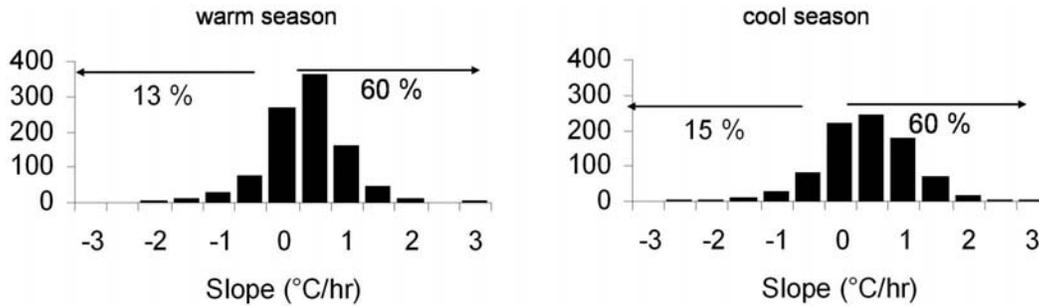
Figure 9 *Frequency of warming and cooling ramps in the two seasons. Positive ramps = warming, negative ramps = cooling.*
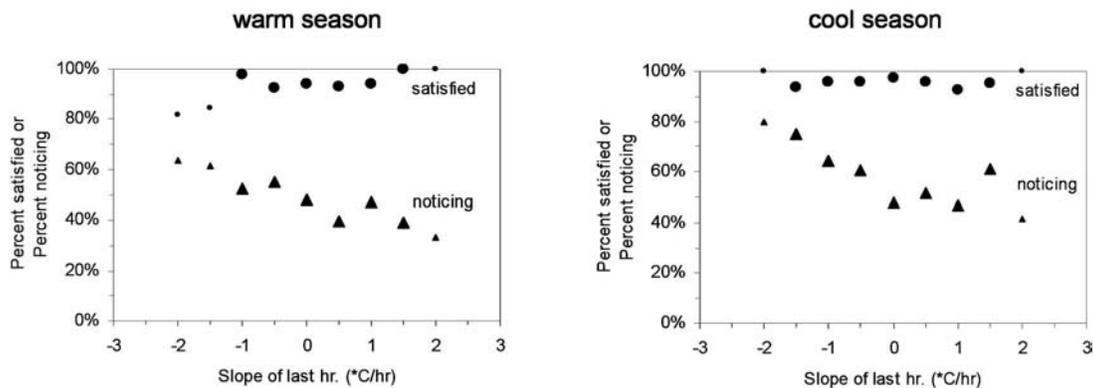

Figure 10 *Percent of people noticing air movement ("a little," "moderate," or "a lot") and percent satisfied (ThSens = –1, 0, 1). Data with less than 15 events per bin are shown with a small point.*

more air movement at this same operative temperature. It is quite likely that this desire for more air movement is partially for a feeling of air freshness that is lacking with the extremely low mean air speeds in this building. This is consistent with the findings from our Background Survey, where "to let in fresh air" was the second most common reason people gave behind "to feel cooler," when asked why they open their windows.

Assessment of Variability

We defined six different operative temperature variability indices associated with the hour prior to each survey event (average, standard deviation, maximum–minimum, end temperature minus start temperature, slope from least squares linear regression of last hour, and R-squared of slope regression). The last hour's standard deviation (*Top,SD*) was the primary measure of fluctuations, while the slope (*Top,slope*) was the primary measure of ramping conditions (positive values = warming, negative = cooling, absolute value = magnitude). The R-squared was used to validate the slope index as a true measure of a ramp. Ultimately, we did not include the "max-min" and "end-start" indices because they were more strongly influenced by extremes and didn't necessarily reveal patterns. Table 3 provides a statistical summary of the *Top,SD* and *Top,slope* for the warm and cool seasons.

Thermal Ramps—Physical Assessment. The *Top,slope* variable provided the best direct comparison to the ramps created in controlled environment chamber experiments and to the non-steady-state limits presented in ASHRAE Standard 55. We found that 58% of the survey events had *Top,slope* values associated with an $R^2 > 0.5$, indicating that a majority of the hourly variability had ramp-like characteristics. Figure 9 shows the percent frequency of positive (warming) and negative (cooling) ramp rates in the two seasons. Although the majority of ramps show warming trends, there were still a significant number of hours with cooling ramps in both seasons. This was counter to our initial expectations, which were that an internal load dominated office building without HVAC would be warming up during most occupied hours. These data give some clues about the physical performance of the building and how window use is affecting interior temperature trends. We found that temperatures followed an inverted U-shape during the day, with warming trends (positive slopes) in the morning, steady conditions (zero slope) close to noon, and then cooling ramps (negative slopes) typically occurring after 2:00 p.m. These temperature variability patterns are tightly linked to outdoor climate, showing that the envelope conditions might override the internal loads in a naturally ventilated building.

Thermal Ramps—Subjective Assessment. Figure 10 shows both the percentage of subjects noticing ramps and the

**Table 6.   Sample Sizes During Repetitive Survey for Subjects with
High and Low Degrees of Control Over the Operable Windows**

	PC_HI			PC_LO		
Season	# subjects	# events (total)	# events (w/ physical data)	# subjects	# events (total)	# events (w/ physical data)
Warm season	27	768	738	11	277	277
Cool season	31	895	805	7	135	85

percentage voting "comfortable" thermal sensations as a function of the magnitude and direction of the ramp rate. The most striking feature of these plots is the strong asymmetry in which a larger number of people notice cooling ramps than warming ramps. For warming ramps, these results are similar to those of Berglund and Gonzalez (1978), who observed that people did not notice ramps less than 0.5°C/h (0.9°F/h). A second interesting feature in Figure 10 is that there was a negligible relationship between the percentage of respondents experiencing satisfactory thermal sensations and the temperature ramps. The slight decrease in satisfaction for cooling ramps in the warm season may not be statistically significant due to the small number of events in those categories. The conventional wisdom within the thermal comfort community has always been that dynamic thermal conditions are of themselves objectionable—that people have a desire for static or steady-state temperatures inside their buildings. But the data in these graphs do not support this presumption at all. A line-of-best-fit applied to the percentage of satisfactory thermal sensation votes in either season in Figure 10 would be approximately a horizontal line—i.e., bearing no trend or relationship with magnitude or sign of temperature ramp during the hour preceding the questionnaire. Based on these findings, we can infer that ramps up to ±1.5°C/h (2.7°F/h) do not cause discomfort (expressed in terms of thermal sensation) compared to steady-state conditions.

Assessment of Personal Control

Each subject was given a "personal control rating" based on his or her physical location in the building and proximity to the window. The availability of personal control over window operation was initially rated into four categories: 1 = direct control (private office); 2 = direct control (open plan desk directly next to window); 3 = indirect control (open plan desk, usually one desk away from window); 4 = no control (open plan desk blocked by exterior private office or high partitions). Initial analyses showed the largest spread between mean values of many survey responses between categories 2 and 3. Consequently, we developed a simpler two-category personal control (PC) rating of:

PC_HI = direct control, both private and open plan (initial categories 1+2)

PC_LO = indirect or no control (initial categories 3+4)

The analysis presented in this paper utilizes this two-category rating. The Final Report (Brager et al. 2004) presents more details about the few specific circumstances where the four-category rating revealed more information. Table 6 shows the number of subjects in our Detailed Study and the number of Repetitive Survey "events" (an event is a time that the survey is taken) for each of these two personal control categories (note that some physical data are unavailable for some survey events, so both counts are given).

Personal Control and Comfort Parameters. Table 7 characterizes the key comfort-related parameters that these two subject groups experienced at the time they took surveys and indices of thermal variability for the hour preceding each survey.   The two-tailed t-test and P-levels assess the significance of the differences between mean values of those two groups. Some of the differences that are statistically significant (CLO in both seasons and MET in warm season) are not large enough to affect thermal sensations and are in fact smaller than typical measurement errors for these parameters. The only comfort parameters that were clearly different for the PC_HI and PC_LO subjects were *Top* and *Va* during the cool season. For the cool season, subjects with lower degrees of control over the window (typically sitting farther away from the perimeter) generally had higher levels of clothing, higher *Top*, and higher velocities. Based on observations and survey comments, there is a chance that in some areas of the building the air velocity from the lower hopper windows flowed in an upward direction, hit the ceiling, and then bounced down on subjects who were sitting farther into the interior zone. A rigorous assessment of interior air movement patterns was beyond the scope of this study. For both seasons, the PC_HI subjects experienced significantly more thermal variability than the PC_LO subjects, and this will be discussed in more detail later.

Personal Control and Thermal Neutralities. Under "Thermal Neutralities" we reported that neutral temperatures for the full group of subjects were 23.0°C (73.4°F) (warm season) and 22.1°C (71.8°F) (cool season). We repeated the analysis for the separate PC_HI and PC_LO subject groups, calculating a weighted linear regression of thermal sensation vs. operative temperature, and then solving those equations for zero thermal sensation ("neutral"). The resulting neutral temperatures for these separate subject groups are shown in Table 8. In the warm season, people with a higher degree of control over the windows (PC_HI) were comfortable at warmer temperatures than the group with lower levels of

Table 7. Mean Values of Comfort Parameters for Subjects with High and Low Degrees of Control Over the Operable windows. (Significance of Difference Is Labeled "Strong" for P-Values Less then 0.05.)

	Mean Values of Comfort Parameters							
	Warm Season				Cool Season			
	PC_HI	PC_LO	t	Significance of ΔHI-LO	PC_HI	PC_LO	t	Significance of ΔHI-LO
CLO	0.72	0.71	0.75	not	0.77	0.80	2.64	strong
MET	1.27	1.26	3.02	strong	1.25	1.25	0.94	not
Top (°C)	24.1	24.3	1.48	not	22.7	24.0	10.99	strong
Va (m/s)	0.09	0.10	1.09	not	0.04	0.11	6.34	strong
Pw (Pa)	1178.4	1195.2	1.06	not	1100.3	1051.4	3.62	strong
$Top,StDev$ (°C)	0.28	0.20	6.33	strong	0.27	0.21	2.73	strong
$Top,slope$ (°C/hr)	0.59	0.43	4.72	strong	0.66	0.49	3.46	strong

"$Top,StDev$" and "$Top,slope$" are based on the hour prior to each survey event and represent the standard deviation and slope from a least squares linear regression of the hour preceding the subject's thermal questionnaire.

Table 8. Thermal Neutralities for Subject Groups with High and Low Control Over Operable Windows. (All Weighted Regression Models Were Significant at the 99% Level Except for Cool Season PC_LO.)

Season	Personal Control	$T_{nuetral}$	R^2
Warm	PC_HI	23	0.94
	PC_LO	21.5	0.48
Cool	PC_HI	22	0.82
	PC_LO	n/a	n/a

control (PC_LO), as indicated by the 1.5°C (2.7°F) difference in their neutral temperature. In the cool season, the PC_LO group did not have a statistically significant regression model of thermal sensation vs. Top and is therefore not included in the table. Our analysis suggests three explanations as to why the regression on the cool season PC_LO dataset was not statistically significant: (1) smaller number of subjects (7 cool vs. 11 warm), (2) the number of survey events is relatively small (85 cool vs. 277 warm), and (3) the measured temperatures coincident with the surveys spanned a small range.

Personal Control and Adaptation. Adaptive theory states that the temperature at which people are most comfortable is related to the temperatures they are used to experiencing, and this is a result of both behavioral adaptation (changes in CLO, MET, and environmental parameters such as air velocity) and psychological adaptation (shifting expectations, which influence subjective response) (Humphreys 1975; Auliciems 1981; de Dear and Brager 1998). We tested this hypothesis by comparing average operative temperature (for the hour prior to each survey) with the neutral temperature for the two groups with different levels of personal control. Figure 11 shows that, in the warm season, both the PC_HI and PC_LO groups were experiencing very similar operative temperatures at around 24°C (75.2°F) during the hour prior to

the questionnaire, yet the people with more control appear to have adapted their neutral temperatures more closely to those experiences. In contrast, during the cool season the PC_HI and PC_LO groups experienced different operative temperatures (the PC_LO group, in the interior zone, experienced 1.3°C [2.3°F] warmer temperatures). But the same pattern of adaptation is seen in the PC_HI subjects in this season, where they again show a neutral temperature very close to the average temperature they have experienced. (The cool season PC_LO data are not shown, since the regression was not statistically significant). PC_HI neutral temperature is within one standard deviation of the mean experienced temperature for 32 out of 38 subjects. PC_LO is outside one standard deviation of experienced for all subjects.

In addition to the similarity of Top, Table 7 showed that, for the warm season, there were very small differences in the comfort parameters between the PC_LO and PC_HI groups. These differences are small enough that they're unlikely to have a perceptible effect on the mean heat balance of these two groups and on the subsequent predictions of thermal sensation derived solely from heat balance based thermal comfort models. Thus, the difference in the neutral temperatures of these two subject groups is simply a measure of the discrepancy in thermal sensations between two populations experiencing the same thermal conditions (i.e., heat balance on their body) but having different levels of control over their environment. This result is consistent with the adaptive comfort hypothesis that shifts in expectations and attitudes about comfort explain the differences in neutralities, rather than any parameters that directly affect the body's heat balance. For comparison, Bauman et al. (1998) also measured approximately 1.4°C (2.5°F) difference in the neutral temperatures of people with high environmental control vs. those without, in this case for a desktop task/ambient conditioning system.`
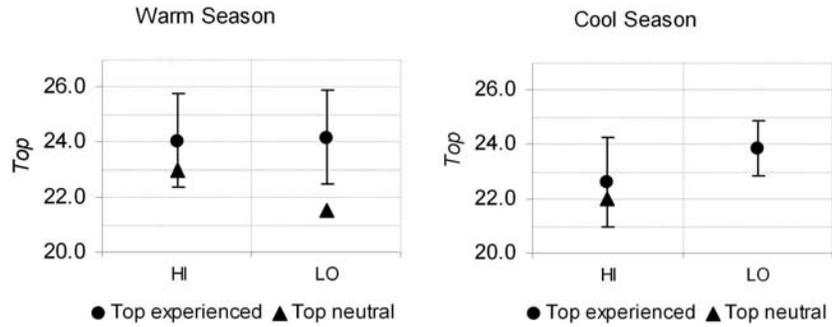
Figure 11 *Experienced temperature compared with neutral temperature. ("Top, experienced" is the average operative temperature for the hour prior to each survey.)*

Table 9. Percentage of Calculated *PMV* Values and Observed Thermal Sensation Votes When *PMV* is Below, Within, and Above the AHRAE Standard 55 Comfort Zone Limits

	Physical Measurements, Percentage of calculated *PMV* values			Survey Responses, Mean thermal sensation votes within bins		
PMV Bins	Cold *PMV* < -0.5	Comfortable -0.5 ≤ *PMV* ≤ 0.5	Hot *PMV* > 0.5	Cold *PMV* < -0.5	Comfortable -0.5 ≤ *PMV* ≤ 0.5	Hot *PMV* > 0.5
Warm season	7.1%	71.5%	21.4%	0.04	0.23	1.21
Cool season	14.0%	78.3%	7.7%	-0.35	0.12	0.07

Comparison to ASHRAE Standard 55

The new ASHRAE Standard 55-2004 (ASHRAE 2004) defines the comfort zone as the combination of air temperature and mean radiant temperature for which –0.5 < PMV < + 0.5. There is no lower humidity limit, and an upper humidity limit (humidity ratio ≤ 0.012) is applicable only for systems designed to control humidity (which this building does not have, but nonetheless there were no measurements above this limit). According to this standard, air velocity should be limited to 0.20 m/s (39.4 fpm), except in circumstances where the occupants have some degree of control over the air velocity (which is the case in this building, through the windows and ceiling fans). In such cases, the standard provides a graph showing the amounts of elevated air speed allowed to offset increased temperatures above the upper limit of the comfort zone (PMV = 0.5). Standard 55-2004 also allows an alternative (optional) compliance path for naturally ventilated buildings based on an adaptive model of comfort. We will be comparing this building to both options.

Physical Measurements, Thermal Sensation Votes, and the PMV-Based Comfort Zone. The extent to which the indoor thermal environment met the ASHRAE Standard 55-2004 PMV-based requirements was assessed by the percent of calculated PMV values (based on physical measurements plus CLO and MET) that fell below, within, and above the limits of PMV = ±0.5 (left side of Table 9). As a way of comparing this predicted comfort index to observed responses, we also calculated the mean thermal sensation vote for each group of subjects falling within each of these PMV categories (right side of Table 9).

The intent of the ASHRAE Standard 55 comfort zone is to specify conditions that at least 80% of the occupants will find acceptable or satisfactory (defined as votes within the three central categories of the seven-point thermal sensation scale). Table 4 shows that 80% to 84% of the subjects were voting "acceptable" thermal sensations. This suggests that, using direct assessment, the building is successfully meeting the *intent* of ASHRAE Standard 55 based on reported thermal sensations. Looking now at the physical measurements and the PMV model, Table 9 shows that roughly three-fourths of the physical measurements fell within the PMV-based comfort zone (slightly more in the cool season, less in the warm season). By this measure, the building appears to be doing slightly better according to the subjects' own responses than might be suggested by a PMV analysis alone.

As might be expected in a passively cooled building, excursions outside the comfort zone were more often in the direction of the outdoor climate of that season (i.e., higher percent of PMV > 0.5 in the warm season and vice versa in the cool season). But thermal sensations did not correspond equivalently to those physical excursions. "Cool" PMV values (PMV < 0.5) occurred 7% to 14% (warm-cool season, respectively) of the time. Yet Table 4 shows that only 2% to 4% of the thermal sensation votes were on the cool side (i.e., PMV predicts that the subjects in the building feel colder than they actually report).

**Table 10. Measured Neutral Temperatures Compared to the
Adaptive Standard's Predicted Optimum Temperatures**

		Subjects	Measured	Predicted (adaptive model),
Warm season		PC_HI	23.0°C	22.9°C
		PC_LO	21.5°C	
		All	23.0°C	
Cool season		PC_HI	22.0°C	21.6°C
		PC_LO	n/a	
		All	22.1°C	

**Table 11. Operative Temperatures and Thermal Sensation Votes Compared to the
Adaptive Standard's Range of Acceptable Temperatures**

	Adaptive Range of Acceptable Top		% Measured Top in Range	
	80% limits	90% limits	80% limits	90% limits
Warm Season	19.4-26.4°C	20.4-25.4°C	87%	75%
Cool Season	18.1-25.1°C	19.1-24.1°C	82%	64%

Air Velocity and Standard 55 Limits. Ninety-three percent of the measured air velocities fell below the ASHRAE Standard 55 limits of 0.2 m/s (39.4 fpm) that apply when people do not have control over air movement. The remaining 7% all occurred simultaneously with warm temperatures and were therefore beneficial for added cooling and were also allowable under ASHRAE's recommendations for elevated air speeds to offset increased temperatures (see Figure 8, which compares measured air velocities to the Standard 55 recommendation as a function of *Top*). Existing velocities were always well below those prescribed maximum limits. Combining this with data at the cool end, where there was a lack of high air velocities coincident with low temperatures and only 3-4% of the responses wanting less air movement, we can conclude that there were negligible problems of uncomfortable draft in this building.

Variability (Non-Steady-State Conditions) and Standard 55 Limits. Our analysis of the frequency distribution of thermal ramps showed that the one-hour ramp rate rarely exceeded the limit of 2.2°C/h (4.0 °F/h), as specified in the revised ASHRAE Standard 55-2004 (only 1% of measurements in the warm season and 1.3% of cool season events exceeded this limit.) It should be noted that the old version of Standard 55-1992 was more restrictive in its limits for non-steady-state conditions, specifying a limit of 0.5°C/h (0.9°F/h). Although this lower limit certainly would have been exceeded more often in this building, our earlier analysis of thermal satisfaction as a function of ramp rates suggests that this limit was overly restrictive, and that ramps up to 1.5°C/h (2.7°F/h) are unlikely to cause discomfort. There were no data to look at people's response to ramps greater than 2°C/h (3.6°F/h).
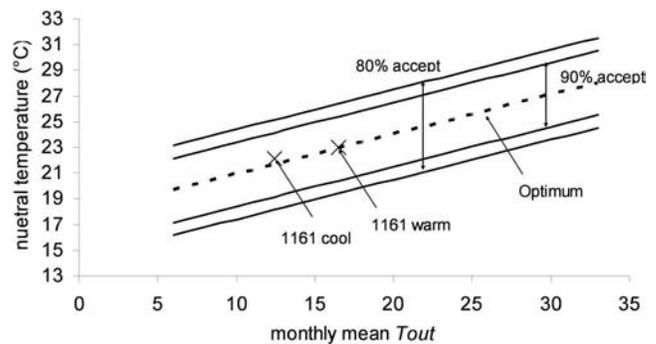

Figure 12 Measured neutral temperature compared to the adaptive standard's predicted optimum temperature.

Physical Measurements, Thermal Sensation Votes, and the Adaptive-Based Comfort Zone. The new ASHRAE Standard 55-2004 (ASHRAE 2004) includes an alternative compliance for naturally ventilated buildings, based on an adaptive thermal comfort model derived from a global database of 21,000 measurements taken primarily in office buildings (de Dear and Brager 2002). The adaptive standard presents the limits of acceptable indoor operative temperature as a function of the mean monthly outdoor temperature of a location. Figure 12 and Table 10 show that the measured neutral temperatures in our building closely match the predicted optimum temperatures ($T_{neutral}$) from the adaptive model (with the match slightly better in the warm season).

In addition to the "optimum," the adaptive model also includes an acceptable range of temperatures, as a function of mean monthly outdoor temperature, based on criteria that either 80% or 90% of the occupants will be comfortable within

those respective ranges. Table 11 shows those ranges of acceptable indoor operative temperatures prescribed by the adaptive standard for our climate and the percentage of measured operative temperatures that fell within each range.

Applying the broader 80% acceptability range of the adaptive model, the building did well in meeting this adaptive standard (82% to 87% of the measurements fell within these limits). The percentage of *Top* falling with the tighter 90% acceptability range (64% to 75%) correlates more closely with the *PMV* limits shown in Table 9 (72% to 78%). In short, the building performs comparably in terms of either the PMV or adaptive thermal comfort criteria, reflecting the fact that the very mild climatic context of the present building didn't stretch the adaptive comfort standard away from the conventional indoor comfort guidelines for air-conditioned buildings.

DISCUSSION

There were only slight seasonal differences in the indoor thermal environment, with a mean indoor operative temperature of 24.1°C (75.4°F) in the warm season and 22.9°C (73.2°F) in the cool season. The min-max range varied similarly: minimum operative temperature was 2.1°C (3.8°F) lower in the cool season, and maximum was 1.9°C (3.4°F) higher in the warm season. Given that this was a naturally ventilated building that also had ceiling fans, air velocities and seasonal differences were both lower than expected. Mean velocities in the warm and cool seasons were, respectively, 0.09 m/s (17.7 fpm) and 0.05 m/s (9.8 fpm). There were no significant differences in seasonal clothing levels for this building, with mean CLO values (including the chair) being 0.7 in the warm season and 0.8 in the cool. This suggests that people may be dressing more for the indoor climate.

Overall, on an aggregate basis the building was fairly successful in maintaining thermal comfort from a variety of measures. The intent of ASHRAE Standard 55 is that at least 80% of a building's occupants should find the conditions thermally acceptable (defined as votes within the three central categories of the seven-point thermal sensation scale). Based on the survey responses (a direct assessment of occupant comfort), 80% to 84% (warm-cool season) of the responses were within these "acceptable" categories, indicating that the building is successfully meeting the intent of ASHRAE Standard 55. Using physical measurements, ASHRAE Standard 55-2004 provides two alternative compliance paths for naturally ventilated buildings to achieve an 80% acceptability rating. Applying the more conservative PMV-based comfort zone, only 72-78% (warm-cool) of the physical measurements fell within the prescribed limits of PMV = ±0.5. Applying the more relaxed adaptive-based comfort zone, a much more satisfactory 86% to 90% (warm-cool) of the *Top* measurements fell within the 80% acceptability criteria. Comparing survey responses and physical measurements, there was a similar percentage of acceptable thermal sensation votes when conditions fell within either the PMV or adaptive comfort zone. This reflects the fact that the mild climatic context of the project building caused the temperature guidelines in the new ASHRAE Standard 55-2004 adaptive comfort method to converge on the prescriptions of the same standard's *PMV* method.

Looking at occupant comfort responses in more detail, it appears that the acceptability of thermal sensations are not symmetric around neutral, and there were clear seasonal differences in terms of people's thermal preferences. "Slightly cool" thermal sensations are more acceptable than "slightly warm" in both seasons with the differentiation being stronger in the warm season. This is similar to the results seen in many earlier field studies (de Dear and Brager 1998) where building occupants preferred thermal sensation shifts with the seasons, commonly called the "semantic artifact." While past research would predict that subjects would prefer to be slightly warm in the cool season, the very mild climate in Berkeley, California, might have diminished the magnitude of this effect. There is some indication that people use the thermal sensation scale as a partial indication of how they would *prefer* to feel (i.e., their votes represent the match, or mismatch, between what they desire or expect and what they experience). In other words, people want to feel "slightly cool" in the summer, and so even if exposed to the same thermal conditions in two different seasons, they are more likely to vote more extreme warmth sensations in the summer than if they experienced those same physical conditions in the winter.

The ideal comfort temperature for a group of people is traditionally determined by the "neutral temperature" (i.e., the temperature at which the mean thermal sensation for a group is "neutral"). Of all the indoor environmental indices, we achieved the highest correlation between thermal sensation votes and operative temperature and subsequently used *Top* as the basis for much of our analysis. In this building, neutral operative temperatures for the full group of subjects were 23.0°C (73.4°F) (warm season) and 22.1°C (71.8°F) (cool season). This was consistent with the adaptive model based on mean monthly outdoor temperature. In fact, the predictions of the adaptive model were within only a few tenths of a degree of the observations we made in these two seasons. These new field data offer more strong support for the adaptive model of thermal comfort and its associated adaptive comfort alternative method in the recently revised ASHRAE Standard 55-2004.

Ideal comfort temperatures were not only influenced by season but by the degree of personal control. Subjects who have more control over thermal conditions of their workplace (in particular, the operable window) had a neutral temperature that was 1.5°C (2.7°F) warmer than subjects with minimal control, even though they experienced the same thermal environments and exhibited no differences in CLO or MET. More importantly, their neutral temperatures more closely approximated the actual level of warmth (mean operative temperature) prevailing in their workplaces, compared to the group of subjects with low or negligible levels of personal control. Given that the two groups were broadly exposed to the same

average thermal conditions, but the group with more control shifted their neutrality closer to their average thermal exposure, this offers the first empirical confirmation of a hypothesis that was offered during the ASHRAE RP-884 project to explain the "shifting thermal expectations" issue. This finding provides clear evidence that subjects with greater access to control are more tolerant of, and in fact may prefer, conditions that may not be in the center of the comfort zone. The corollary of this, witnessed in countless thermal comfort studies in air-conditioned offices, is that people who have limited or no control over their office thermal environment, as is the case in the vast majority of air-conditioned office buildings, tend to be less tolerant and accepting of suboptimal thermal environmental conditions.

The role of air movement in occupant comfort, and particularly in naturally ventilated buildings, is significant. Understanding the impacts of personally controlling air movement to optimize individual comfort has implications for other types of buildings and systems as well (such as task/ambient systems where workers have control of local diffusers). Our results confirm previous findings by others that occupants are able to sense relatively low air speeds. Negative sensations of draft were essentially nonexistent in this building. In contrast, people who preferred a change in air movement were nearly always asking for more (especially in the warm season), not less. Preference for air movement is strongly related to thermal sensation, showing that people want to control air movement as a means for improving their comfort. In this particular building, however, the available air movement was not sufficient to offset temperature increases when they occurred. During the times that Top was high, and thermal sensation votes were +2 or +3, the measured air speeds were well below the recommendations in both ASHRAE Standard 55-1992 and 55-2004 for elevated air speeds to offset a rise in temperature. And given the lack of complaints of draft, these findings suggest that occupants would happily accept higher levels of air movement over which they have control, and they are quite likely to use it appropriately to keep themselves comfortable. This lesson is perhaps applicable to other buildings as well, to encourage designers to provide air movement as a low energy cooling strategy and to ensure that sufficient levels of air movement are available.

The acceptability of variability (in this case, naturally occurring thermal ramps) also revealed an asymmetry. More subjects tended to notice cooling ramps (temperature decreasing) compared to warming ramps. There appears to be no relationship between the thermal satisfaction and ramp rate within the range experienced in this building, suggesting we may be overestimating people's desire for static conditions.

CONCLUSIONS

The objective of this work was to investigate how operable windows affect the indoor thermal environment and occupant comfort, with a particular interest in the influence of air movement and thermal variability. We conducted a field study in a naturally ventilated office building, during two seasons (warm/cool), to investigate how personal control of operable windows influences thermal conditions and occupant comfort. In addition to a Web-based Background Survey administered to all occupants of the building, thirty-eight subjects participated in a Detailed Study, consisting of two-week monitoring periods during each of the two seasons. During that time, our methods included continuous measurement of each subject's workstation microclimate, plus a web-based Repetitive Survey that subjects took several times a day and cross-linked to concurrent physical assessments of workstation microclimatic conditions. We collected over 1000 survey responses in each of the seasons.

We found that occupants experienced surprisingly similar thermal environments (as well as CLO and MET levels), independent of the proximity to and degree of personal control they had over the operable windows. Despite the similarity of thermal exposures, however, their reactions were significantly different. Ideal comfort temperatures (defined by the "neutral" temperature) for the occupants with higher degrees of control were much closer to the temperatures they actually experienced, providing direct support for the adaptive comfort hypothesis that thermal preferences are based, not just on conventional heat balance factors, but a shifting of expectations resulting from higher degrees of control over their own environment.

The significance of this RP-1161 conclusion is that it directly refutes much of the skepticism surrounding the original ASHRAE-funded adaptive model project RP-884 (de Dear and Brager 1998). The fact that we obtained this finding in California, and not an impoverished third world country, dismisses the ethnocentric criticisms aimed at the adaptive comfort model over the last decade. Our present findings demonstrate that it is clearly possible to design low energy, naturally ventilated office buildings that will be thermally acceptable to discerning occupants with experience of the fully air-conditioned alternatives. The findings also reinforce the notion that the wider range of temperatures permitted under the adaptive version of the new standard will only meet with occupant acceptance if those occupants have access to adequate adaptive opportunities (i.e., personal control of environmental conditions). Our findings suggest that the wide-ranging acceptable temperature limits in the adaptive comfort standard are not appropriate for mechanically regulated buildings where occupants have negligible direct thermal control. It is critical that buildings be designed so that occupants can be active participants in the indoor climate feedback loop, not simply passive recipients of whatever thermal conditions the building management system delivers.

This study also suggests strategically valuable avenues of further research. Now that we have a clearer picture of the importance of thermal control and adaptive opportunity in comfort theory, it would be useful to extend the study methods developed in this project to a more extreme climatic setting in

which the test building experiences more extreme temperature excursions above the conventional comfort range.

ACKNOWLEDGMENTS

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DISCUSSION

Bjarne Olesen, Professor, Department of Mechanical Engineering, DTU, Lyngby, Denmark: Even if 75% of people open windows daily, how come the air velocity was less than 0.1 m/s?

Gail Brager et al.: Air movement (as measured on people's desks) was lower than we expected in this building, given the frequency with which people opened their windows in both seasons. We have confidence in the accuracy of the measurements given that the sensors were brand new, factor calibrated, and verified in the lab. Mean air speed was 0.09 m/s (warm season) and 0.05 m/s (cool season); maximum air speed was 0.95 m/s (warm season) and 0.75 m/s (cool season); and 90% of the measured air speed fell below 0.15 m/s. Although a detailed study of air movement patterns was beyond the scope of this study, it's possible that the design of the lower hopper windows (which were used much more often than the upper casement windows) caused the air to flow upward and air speed past the desktop sensor may have been lower than people experienced at head level, or the air might have even flowed upward and over the occupied zone. This building has a large percentage of the facade that can be opened, implying that the mean speed across any opening could be low while still providing the needed air changes. It has been noted by other researchers (Nichol, Humphreys) that many field studies in naturally-ventilated buildings have found air velocities in a similar range to those that we measured.

Jin Wen, Assistant Professor, Drexel University, Philadelphia, Pa.: What do you think about the future R&D areas and priorities in this area?

Brager et al.: Based on a question Professor Wen asked us directly after the symposium, we believe that she is specifically asking us to reiterate the summary comments we made at the end of the session. We were referring to four R&D needs specifically raised by the symposium's collective presentations.

1. *Tools for subjective assessment.* The thermal comfort literature is fraught with terms such as *thermal sensation*, *preference*, *comfort*, *satisfaction*, *acceptability*, *neutrality*, etc. In the absence of solid research, we rely on assumptions and vague associations to define the relationships between these different constructs. In particular, ASHRAE Standard 55 specifies conditions that occupants will find thermally "acceptable," and it relies on professional judgment to deem that "acceptable" means 80% "comfortable"; it defines thermal "comfort" as a condition of mind that expresses "satisfaction," yet "satisfaction" is simply assumed to be associated with the three middle categories of the 7-point "sensation" scale. In short, the engineers in our field would benefit from increased collaboration with, and contributions from, environmental psychologists to tighten our definitions of what "thermal comfort" really means in the minds of ordinary building occupants.

2. *Behavioral models in energy simulation programs.* State-of-the-art energy simulation programs treat occupants merely as components of the building's internal loads, at best modeling only the dynamic occupancy patterns during the day. As we strive to optimize both comfort and energy use, and design buildings that are responsive to climate and context, we need better ways to quantify the ways in which people interact with the building, modify their own environment, and play a vital role in that optimization. Modeling the old adage, "passive buildings require active occupants," will be required in the next generation of energy simulation programs.

3. *The role of control.* An increasing number of people are accepting, and even promoting, the use of individual thermal control through operable windows, task/ambient conditioning systems, or other forms. The questions no longer center around "should we devolve thermal control," but instead are focused on "how to effect it." Effort needs to be spent on developing new products and technologies, educating architects and engineers, documenting and reducing costs, and re-evaluating building fire codes that are often a significant barrier to incorporating such technologies. There are also many issues that thermal comfort researchers need to address, with the aim of providing alternative recommendations for acceptable thermal conditions when occupants themselves are able to control those conditions. There is also evidence in the literature that energy efficiency can be improved when people are given control of their environment because energy use was more closely allied to needs rather than maintaining uniformity based on externally-imposed standards regardless of occupant requirements. Other researchers have found that fewer building-related ill health symptoms and greater productivity were achieved as the perceived level of individual control increased. The impact of personal control cannot be underestimated, but clearly needs to be investigated further so we can understand its impact on comfort, health, productivity, and energy use, and how we can best incorporate it into our buildings.

4. *Beyond thermal neutrality.* Thermal comfort standards and mechanical engineers designing environmental control systems typically strive to provide neutral thermal conditions that are constant in time and uniform throughout the environment. The goal is often to avoid the negative and minimize dissatisfaction. Perhaps we should be aiming for a higher level of experiential quality in our environments, where "pleasantness" and "delight" rather than "neutrality" are the goals. Researchers also need to take a more integrative view of the indoor environment. With few exceptions, most studies look at one outcome at a time and try to assess what the ideal environmental conditions would be for optimizing thermal comfort, indoor air quality, energy consumption, or productivity. Such narrowly defined scopes often produce findings that suggest conflicting goals for the indoor environment. There is a need for more research into how we can optimize a variety of environmental attributes simultaneously.

Fergus Nicol and Michael Humphreys, Oxford Brookes University, Oxford, UK: (1) By emphasizing the "expectation" aspects of the adaptive model, we feel this otherwise excellent paper does not bring out the essential dynamic of the process. Could you present the use of environmental controls (especially windows and fans) for comparison with the results given in our paper (NA-04-2-3) in the same symposium (reference follows)?

Nicol, J.F., and M.A. Humphreys. 2004. A stochastic approach to thermal comfort—Occupant behavior and energy use in buildings. To be published in *ASHRAE Transactions* 110(2).

(2) What is the significance of the difference in comfort temperatures in between the HI and LO control groups? Is there a significant difference in the rate of reported discomfort between these groups?

Brager et al.: (1) While it's beyond the scope of this question and answer format to present additional analysis, we will try to summarize some of our findings verbally. The objectives and type of data collected in our study and your own were also slightly different, so our analysis may not be directly comparable. We gathered a large amount of data, and the final report includes a much more extensive set of analyses that we were able to present in either our technical or symposium presentation. We examined various behavioral adaptive mechanisms, such as clothing changes and adjustments to windows,

fans, heaters, etc. We can offer some of the results from our final report here.

1. Operable windows were, by far, the most used control. Blinds were used about half as often as windows, and ceiling fans or desk fans were used even less. One reason the ceiling fans may not have been used often is that they were primarily located above the corridors rather than the workstations, and so were not as effective as they might otherwise have been. There were very few desk fans in the building.

2. People reduced their clothing insulation (including chair insulation) linearly with temperature down to a minimum Clo of 0.7 around 26°C (presumably the socially acceptable limit).

3. Measured air speeds started to increase at an operative temperature of 24.5°C, presumably because people were using more windows and ceiling fans.

4. Occupants' use of windows had a measurable immediate effect on space temperatures and a smaller effect on the long-term temperature trends.

5. Window usage patterns during the warm season were analyzed and reported in more detail in two other papers referenced below (Inkarojrit 2003; Inkarojrit and Paliaga 2004). The percentage of open windows spanned a wide range (from 5% to –50% at any one time), and was linearly correlated with operative temperature in the range of 22-26°C. People clearly interacted with the building in a way to maintain comfort.

Our primary objective in this project was to examine the differences between individuals with relatively high (HI) and low (LO) degrees of control in the same naturally-ventilated building. Interestingly, we found that there were few differences in the clothing, activity, and physical conditions that the HI and LO control groups experienced as a result of their behavioral adaptation, even though their ability to adjust certain environmental conditions were different. So while these two groups were experiencing similar physical conditions that influenced their heat balance, we found significant differences in their subjective response, which can be attributed to differences in the degree to which they perceived those comparable physical states to be comfortable. We believe that this illustrates that, while behavioral mechanisms are certainly significant in allowing people to adjust their personal comfort, psychological dimensions are also relevant to the degree of

thermal comfort experienced. This emphasizes the importance of not just designing a *building* with a high degree of adaptive opportunity (including, but not limited to, operable windows), but ensuring that all *occupants* have direct and easy access to those various means to control their own environment. Future revisions of thermal comfort standards should strive to incorporate the broader impacts of adaptive opportunities, such as various means of personal control over environmental systems, flexible dress codes, etc.

Inkarojrit, V. 2003. Occupants' control of operable windows in naturally-ventilated office building: A pilot study. *Proceedings of the 28th National Passive Solar Conference, Austin, Tex.*

Inkarojrit, V., and G. Paliaga. 2004. Indoor climatic influences on the operation of windows in a naturally ventilated building. Submitted for review. Plea2004—The 21st Conference on Passive and Low Energy Architecture. Eindhoven, The Netherlands, September 19-22, 2004.

(2) In the warm season, people with a higher degree of control over the windows (PC_HI) were comfortable at warmer temperatures than the group with lower levels of control (PC_LO), as indicated by the 1.5°C difference in their neutral temperature.

Season	Personal Control	$T_{neutral}$	r^2
warm	PC_HI	23.0	0.94
	PC_LO	21.5	0.48
cool	PC_HI	22.0	0.82
	PC_LO	n/a	n/a

The difference in the neutral temperatures of these two subject groups is truly a measure of the discrepancy in perceived thermal sensations between two populations experiencing the same thermal conditions, but having different levels of control over their environment. This result goes to the core objective of the current project and is consistent with the adaptive comfort hypothesis that shifts in perceptions and attitudes about comfort explain part of the differences in neutralities rather than exclusively any the parameters directly affecting the body's heat balance.