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Air Quality and Thermal Comfort in Office Buildings: Results of a Large Indoor Environmental Quality Survey

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Summary: *This paper presents results of over 34,000 survey responses to air quality and thermal comfort questions in 215 buildings in US, Canada, and Finland. Results show that 80% or more of the occupants expressed satisfaction with their thermal comfort in only 11% of the buildings surveyed. Air quality scores were somewhat higher, with 26% of buildings having 80% or occupant satisfaction. With respect to thermal comfort and air quality performance goals set out by standards, most buildings appear to be falling far short. Occupant surveys offer a means to systematically measure this performance, and also to provide diagnostic information for building designers and operators.*

Keywords: *Indoor environmental quality, thermal comfort, air quality, occupant survey, productivity*
Category: *Design and operation of healthy buildings*

1 Introduction

Indoor air quality and thermal comfort are two important aspects of indoor environmental quality that receive considerable attention by building designers. International and regional standards prescribe conditions intended to foster environments that are acceptable to occupants. Although there is considerable field data on air quality and thermal comfort [1,2], there is far less data that assesses occupant satisfaction across a large number of buildings using a systematic method, and using occupant opinions as a measure of building performance is still far from standard practice [3].

For the past several years, the Center for the Built Environment (CBE) at the University of California, Berkeley has been conducting a web-based indoor environmental quality survey 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 [4]. The questions asked in the survey have remained consistent over time to create a standardized database for benchmarking and analysis. This paper presents an analysis of the air quality and thermal comfort questions.

2 Research Methods

Results from the CBE survey database as of October 1, 2005 were used for the analysis. This data is comprised of responses from 34,169 occupants in 215 buildings throughout North America and Finland.

The data collected through the CBE survey can be divided up into subjective and objective variables. The objective variables measured include gender, age group, type of work, office type, proximity to windows and exterior walls, and various types of control over workspace environment, such as thermostats. The subjective variables measured include occupant satisfaction and self-reported productivity with the IEQ categories. In satisfaction and self-reported productivity questions we use a 7-point semantic differential scale with endpoints "very dissatisfied" and "very satisfied." For the purposes of comparison, we assume the scale is roughly linear, and assign ordinal values to each of the points along the scale, from -3 (very dissatisfied) to +3 (very satisfied) with 0 as the neutral midpoint. Figure 1 shows an example of the satisfaction scale question. In the event where respondents vote dissatisfied to a satisfaction question on the survey, they are taken to a follow-up page containing drill-down questions about the source of dissatisfaction, and a text box for open-ended comments.

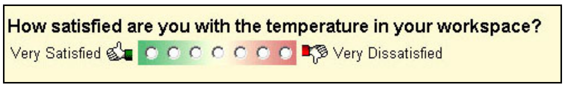

Figure 1 – Typical 7-point satisfaction scale in survey

Of the 215 buildings surveyed so far, 90% are located in the United States, the remainder in Canada and Finland. About 80% of the buildings we have surveyed are owned or leased (and primarily occupied) by some government entity (federal, state or local). All are office buildings, with 22% providing some additional functionality, such as courthouse, bank, educational, or laboratory.

Occupants in each building are invited to take the survey once over a two-week period through an invitation e-mail including the URL that links to the survey. The survey has been conducted across seasons, but the majority of responses in our database were collected in the summer season. The average response rate was 46%.

This paper focuses on occupant satisfaction with thermal comfort and air quality as well as self-reported productivity impacts. A satisfaction score for each building is calculated as the mean satisfaction vote of the occupants in that building. Similarly mean satisfaction scores for the entire database have been computed by averaging the scores for each building.

3 Results

Figure 2 presents the average building scores for each category in the survey across the entire CBE database. The average acoustics score (-0.2) is the lowest of all of the categories. Jensen [5] has previously analyzed results from this category in detail. Thermal comfort (-0.1) and air quality (0.31) have the next lowest scores, and analysis of these categories is the topic of this paper.

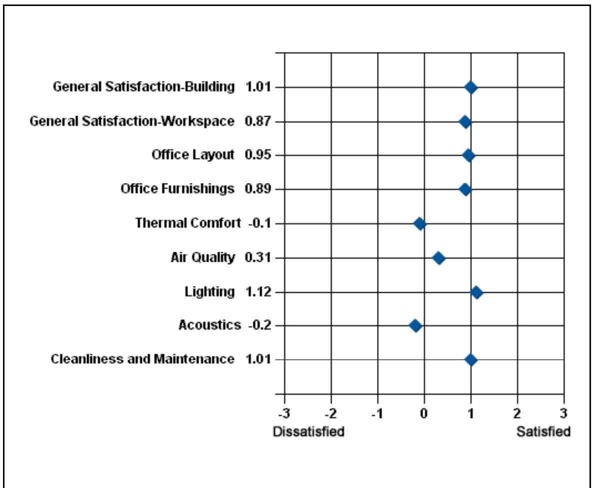

Figure 2. Average building scores by category in CBE survey database (215 buildings, 34,169 responses)..

Thermal Comfort

Figure 3 shows the distribution of thermal comfort satisfaction scores for all occupants. Overall, more occupants are dissatisfied (42%) than satisfied (39%), with 19% of occupants neutral. Of note is the relatively high percentage of responses in the –2 and -3 categories (27%). For reference, the distribution of response for overall workspace satisfaction is presented in Figure 4.

Another way to illustrate this trend is to look at the proportion of occupants satisfied with temperature in each building, and plot these in a frequency distribution (Figure 5). We see that in just 11% of the buildings, 80% or more are satisfied with temperature in the workspace.

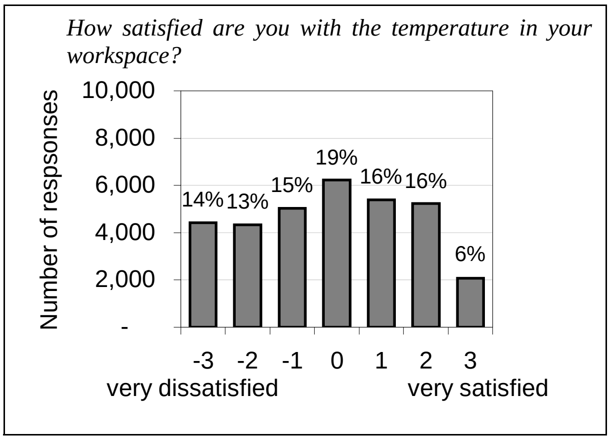

Figure 3. Distribution of termperature satisfaction votes across all occupants.

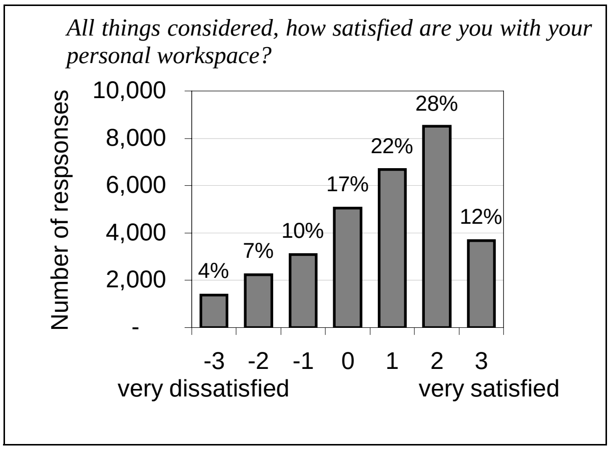

Figure 4. Distribution of workplace satisfaction votes across all occupants.

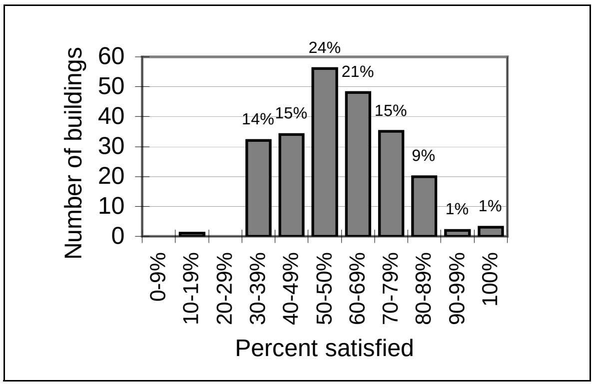

Figure 5. Distribution of temperature satisfaction rates (percent of occupant votes >=0) for all buildings.

The survey's follow-up pages provide valuable information about why occupants tend to be dissatisfied with thermal conditions. Occupants who vote <0 on temperature satisfaction were presented with diagnostic questions about the sources of their dissatisfaction. Figure 6 shows a list of sources of dissatisfaction ranked by frequency of selection. The three most frequently indicated problems are all related to inadequate control.

We further analyzed the results by comparing temperature satisfaction for those occupants who had control over some aspect of their thermal environment to those who did not. Table 1 shows the mean temperature satisfaction and % satisfied votes for groups of occupants with and without access to a thermostat, operable window, portable heater or portable fan. The differences are significant even when controlling for other factors that could influence temperature satisfaction, such as office type (private, shared and open plan) and gender. The most striking result is the improvement in satisfaction of 0.93 for those occupants that had access to a thermostat. This result is consistent with other studies that have demonstrated improved satisfaction with personal control [6,7]. Of particular note is that 76% of all occupants with a thermostat were satisfied with the temperature in their workspace as compared to 56% satisfaction for those without a thermostat. Operable windows also significantly increase satisfaction with temperature. Occupants with portable heaters and fans had lower satisfaction than those without. Presumably the presence of these devices indicates a deficiency with the building HVAC system.

Table 1. Mean temperature satisfaction votes and % satisfied for groups with and without controls. All differences are statistically significant (p<0.01)

	Mean temperature satisfaction vote	% satisfied*	N
all occupants	-0.15	58%	32,749
no thermostat	-0.23	56%	29,313
thermostat	0.70	76%	3,437
difference	*0.93*	*20%*	
no operable window	-0.19	57%	30,018
operable window	0.31	67%	2,732
difference	*0.50*	*10%*	
no portable heater	-0.08	59%	29,435
portable heater	-0.74	44%	3,315
difference	*-0.66*	*-15%*	
no portable fan	-0.06	60%	25,422
portable fan	-0.44	51%	7,328
difference	*-0.38*	*-9%*	

** those occupants voting >=0 on the –3 to +3 satisfaction scale*

Those occupants who were dissatisfied with the temperature in their workspace were also asked whether their workspace was too hot or too cold in warm and cold weather (Table 2). One striking result is that there are approximately the same number of hot and cold complaints in warm weather. This suggests that there may be a large potential to improve comfort and reduce energy in those buildings with a significant number of cold complaints in warm weather.

Table 2. Hot and cold complaints by season. (Note that only those people dissatisfied with the temperature in their workspace were asked these questions).

	In warm weather	*In cold weather*
Often too hot	5,546	3,678
Often too cold	5,450	6,667
Often too hot and often too cold	1,444	1,156

Air Quality

Air quality satisfaction is somewhat higher then thermal satisfaction in the buildings we surveyed. Figure 7 shows the distribution of air quality satisfaction votes across all occupants. In contrast to the thermal satisfaction votes, more occupants voted >0 (45%) then <0 (32%), and the average vote was positive (0.17).

Turning to the data collected by the air quality diagnostic page, presented to those dissatisfied with air quality, 74% rated "air is stuffy/stale" to be a major problem, 67% rated "air is not clean" to be a major problem, and 51% rated "air smelling bad (odors)" to be a major problem. The three most frequently identified sources of odor were food, carpet or furniture, and other people.

The average air quality satisfaction vote for occupants with operable windows (N=2,668) was 0.48 compared to 0.14 for those without operable windows (Table 3).

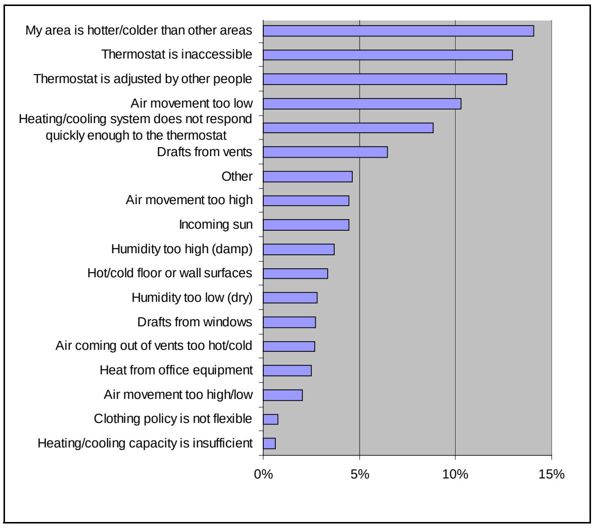

Figure 6. Sources of dissatisfaction with workspace temperature ranked by frequency of occurence (occupants could select multiple causes).

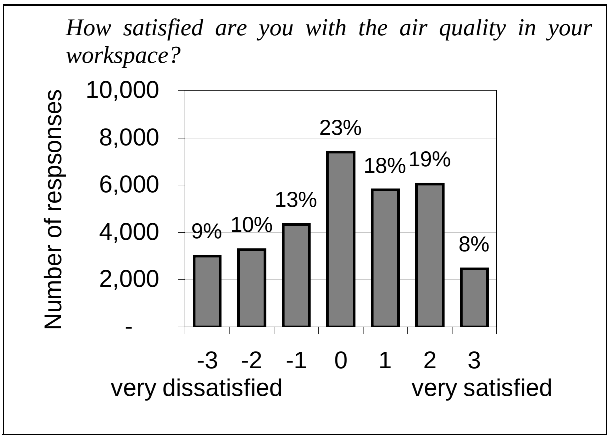

Figure 7. Distribution of air quality satisfaction votes across all occupants.

Table 3. Mean air quality satisfaction votes and % satisfied for occupants with and without operable windows. All differences statistically significant (p<0.01)

	Mean air quality satisfaction vote	% satisfied*	N
all occupants	0.17	67%	32,749
no operable window	0.14	67%	29,632
operable window	0.48	73%	2,668
difference	*0.34*	*6%*	

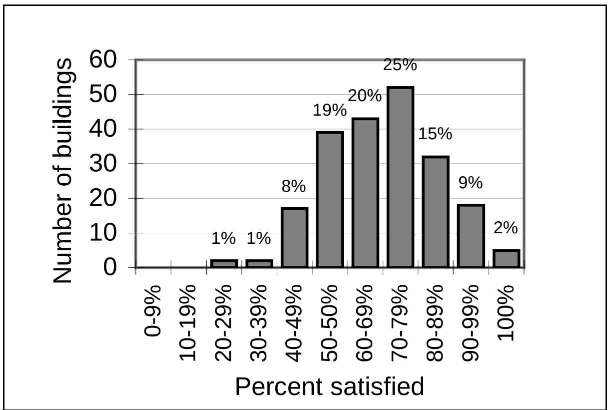

Figure 8. Distribution of air quality satisfaction rates (percent of occupant votes >=0) for all buildings.

Self-assessed productivity

Both thermal comfort and air quality can have important impacts on productivity [7,9]. In addition to the satisfaction questions, the survey asks occupants to rate the impact of each environmental category on their productivity. The thermal comfort productivity question is shown in Figure 9. The same format was used for air quality with the text "Overall, does the air quality in your workspace enhance or interfere with your ability to get your job done".

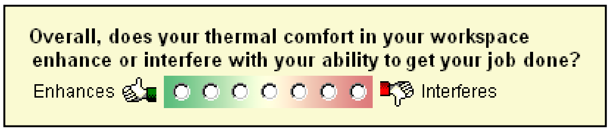

Figure 9. Self-assessed productivity question for thermal comfort.

We found a very high correlation between satisfaction and self-assessed productivity impacts. Figure 10 shows the average thermal comfort productivity response binned by satisfaction response for entire database. A linear regression yields the following relationship ($R^2 = 0.99$):

$$\text{Productivity vote} = 0.84 \cdot \text{Satisfaction vote} + 0.03$$

For air quality, the result was very similar (slope=0.80, intercept=0.07).

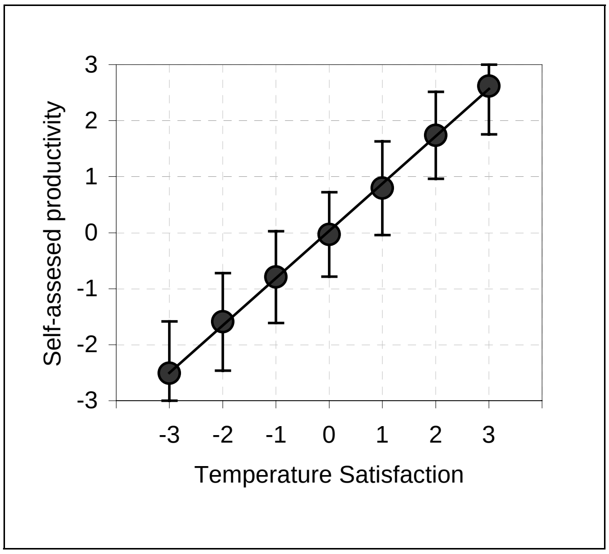

Figure 9. Average self-reported productivity binned by satisfaction votes for workspace temperature.

4 Discussion

With respect to thermal comfort and air quality goals 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 [10]. ASHRAE Standard 55-2004 defines the same limits but recognizes that local discomfort and asymmetries could produce an additional 10% dissatisfaction [11]. Our survey results clearly indicate that much higher rates of dissatisfaction occur in buildings. Figure 5 show the distribution of satisfaction rates (percentage of occupants voting >= 0) by buildings in the database. Only 11% of buildings had 80% or more satisfied occupants. The mean building satisfaction rate is 59% (st. dev. 16%).

ASHRAE Standard 62.1-2004 defines acceptable air quality as conditions in which more than 80% of people do not express dissatisfaction [12]. Analysis of our database shows that 26% of buildings meet the intent of this standard. Figure 8 shows the distribution of the percentage of occupants in each building voting >=0 on air quality satisfaction. The average building satisfaction rate is 69%.

We show very clearly that personal control over environmental conditions (e.g., thermostat or operable window) has a significant positive impact on occupant satisfaction. One means of achieving higher occupant satisfaction would be to provide such control to more occupants.

In the past, occupant complaints to facilities staff [13] have been one of the few ways to assess a building's performance. Occupant surveys provide a standardized and systematic method for assessing occupant satisfaction with the indoor environment. They also provide a means for collecting diagnostic information to help identify problems. This can be done for an individual building in detail, or to learn about trends across many buildings.

The results of this study show the state of indoor environmental quality in office buildings, and highlight the importance of post occupancy evaluation. This information has important implications for how buildings are designed, built, and operated to increase occupant comfort and productivity.

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