Are Humans Good Sensors?
Using Occupants as Sensors for Indoor Environmental Quality Assessment and for Developing Thresholds that Matter

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ABSTRACT

The indoor environmental quality (IEQ) of buildings can have a strong influence on occupants' productivity and health. Post occupancy evaluation (POE) is the first step in assessing IEQ, and typically relies on subjective surveys of thermal quality, air quality, visual quality, and acoustic quality.

This research has expanded POE to include both objective IEQ measurements and the technical attributes of building systems (TABS) that may affect indoor environment and user satisfaction (POE+M). The suite of three tools including user satisfaction survey, TABS and workstation IEQ measurements in the National Environmental Assessment Toolkit has been deployed in over 1,600 workstations in 64 buildings, generating a rich database for statistical evaluation of the possible correlations between the physical attributes of workstations, environmental conditions, and user satisfaction.

As such, this research implemented an integrated approach to POE+M by leveraging occupants as sensors to quickly capture IEQ conditions in a work environment. This approach can identify critical factors in the physical environment that impacts occupant comfort and satisfaction. This approach provides practical IEQ assessment methods and procedures centered on the occupants' perspective. The ultimate outcome of this research will contribute correlations between occupant perception and measured data, a refined survey method to assess building IEQ capable of robust prediction of building performance, and metrics and guidelines for IEQ standards that capture new thresholds that impact occupants' comfort.

Multivariate regression and multiple correlation coefficient statistical analysis revealed the relationship between measured and perceived IEQ indices, interdependencies between IEQ indices and other satisfaction variables of significance.

1. Introduction

Given our modern sedentary lifestyles, people spend most of their time indoors. For Americans it is 22 hours per day, and for Europeans it is 20 hours a day (BLS, 2011). Given the tiny amount of time we now spend outdoors, the indoor environmental quality (IEQ) of buildings has a strong influence on our productivity and health (Fisk, 2002; Loftness et al., 2009). Numerous studies have indicated that indoor environmental quality including thermal, air, visual and acoustic conditions in the workspace is critical for occupant health and productivity (Fisk, 2002; Alan Hedge, 2000; Meir, Garb, Jiao, & Cicelsky, 2009; Mendell et al., 2002; Wargocki, Wyon, Sundell, Clausen, & Fanger, 2000).

Currently, post occupancy evaluation (POE) is the first step in assessing IEQ, and typically relies on subjective surveys of thermal quality, air quality, visual quality, and acoustic quality (Fisk, 2002; Alan Hedge, 2000; Meir, Garb, Jiao, & Cicelsky, 2009; Mendell et al., 2002;

Wargocki, Wyon, Sundell, Clausen, & Fanger, 2000). Subjective POE surveys should be complemented by objective measurements (POE+M) to judge both subjective and objective conditions that maybe impact health and productivity (Loftness et al., 2009; Newsham et al., 2009; Park, 2013; J. A. Veitch, K. E. Charles, K. M. Farley, & G. R. Newsham, 2007).

The goal of this research is to develop and design guidelines to enhance user satisfaction by providing optimized individual IEQ components. Toward this research goal, the following research objectives were established.

- To identify critical IEQ and physical factors for occupant satisfaction.
- To identify correlations between building systems, measured IEQ, and user satisfaction in concurrent time frames.
- To identify where humans are effective sensors for POE+M and to modify standards and thresholds.

2. Method

Carnegie Mellon University (CMU)'s Center for Building Performance and Diagnostics (CBPD) has collected objective and subjective data on the IEQ at individual workstations with public and private sector buildings. The building performance dataset that has been gathered includes technical attributes of building systems, user satisfaction survey results, and workstation IEQ measurements as shown in Figure 1.

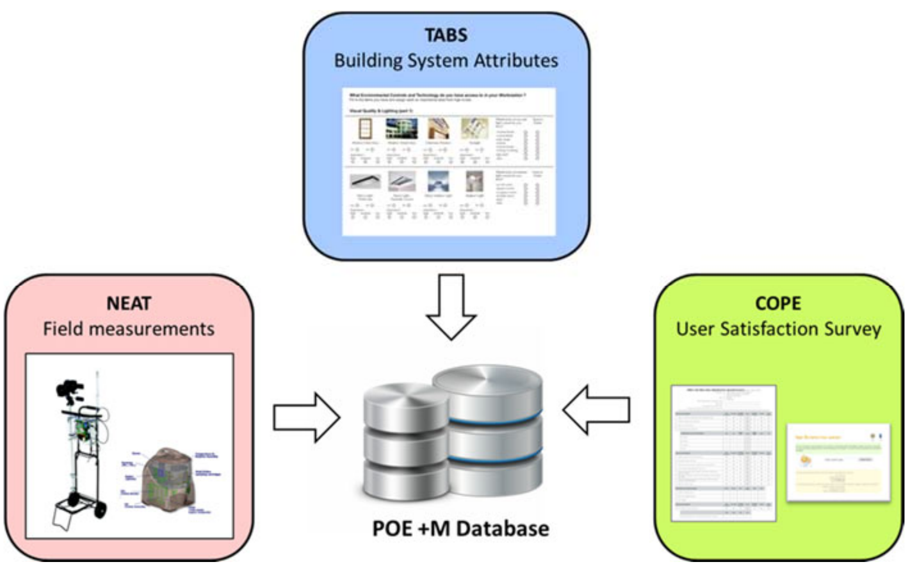

Figure 1 CMU's 3 dataset and POE + M database

The purpose of creating a database is to explore the correlation between occupants, technical attributes of building systems, and measured indoor environmental quality. It can be helpful for facility managers and architects to identify which of these variables have direct or indirect impact on an office worker's perceived satisfaction regarding thermal, air, visual and acoustic quality. A new database was created based with POE field data from 2003 to 2014. A total of 1,601 workstations from 64 buildings were selected according to the following criteria:

- Region: USA (57) and Europe (7)
- Type of organization: federal offices and R&D centers performing intensive office work, private sector financial, sales and marketing companies
- Size of office: small and medium sized office (less than 5,000 ft^2, 465 m^2)

Three different kinds of data were collected to construct a database: occupant satisfaction surveys (COPE), technical attributes of building systems (TABS), and workstation IEQ measurements (NEAT). Each workstation had a unique space ID, which is linked exclusively to thermal, air, visual, acoustic, and spatial quality survey data. In total, 29 COPE variables, 110 TABS variables, and 15 NEAT variables were combined in MySQL.

Statistical analyses, which were the main method for this research, were performed using the statistical software packages SAS (v.9.3) (SAS Institute, 2011) and STATA (v.13) (StataCorp, 2013). Data screening is the process that we used to ensure that the data are clean and ready for conducting further statistical analyses (O'brien, 2007). Data preparation and screening were conducted following Baron and Kenny (Baron & Kenny, 1986). Among 1,719 data points, data from 118 workstations were dropped after being identified as multivariate outliers, leaving 1,601 cases for analysis. In each variable, missing values were ignored. The data indicates four critical variables as mentioned in the extensive literature review. The four critical variables included in the data analysis were as follows:

- **Season (i.e. heating, cooling, and swing season)**: Depending on the season, buildings run different HVAC systems (heating or cooling) and people wear different types of clothing. According to Fanger's comfort equation, clothing is a critical factor in thermal comfort (Fanger, 1970; A. Hedge & Erickson, 1997). It is expected that the season needs to be considered to assess perceived thermal comfort.

- **Gender**: There is a significant difference between men and women in thermal dissatisfaction (Karjalainen, 2007). This difference between the genders may be due to clothing insulation and metabolic differences, so gender was considered in the data analysis.

- **Perimeter vs. Core workstation**: Occupants working in perimeter offices have shown higher user satisfaction than those working in the core. The location of the workstation needs to be considered for perceived user satisfaction. Since the environmental variables such as view, thermal control, and air movement, and so on, are quite different between perimeter and core workstations, it is expected that the location of the workstations needs to be considered for perceived user satisfaction.

- **Open-plan and closed office**: It has been shown that open-plan office occupants are more satisfied with their environments than closed office occupants (J. A. Veitch, K. E. Charles, K. M. J. Farley, & G. R. Newsham, 2007). It is expected that occupant satisfaction may be related to privacy and control issues in the office, so the office types were considered in the analysis.

3. Results

3.1 Thermal Quality

Given the NEAT database of 1,197 workstations in 64 buildings, overall, 55 % of occupants responded 'satisfied' or 'neutral' and 45% of occupants reported 'dissatisfied' with their thermal conditions. The average temperature satisfaction is 3.5, which falls between 'somewhat dissatisfied' and 'neutral' with their temperature satisfaction on a 7-point scale (very dissatisfied, dissatisfied, somewhat dissatisfied, neutral, somewhat satisfied, satisfied, and very satisfied) survey. This suggests that the analyzed offices did not meet the ASHRAE 55 thermal comfort acceptability standard of 80% (ANSI/ASHRAE, 2010) . The analysis showed that six factors (window quality, size of zone, level of thermal control, air temperature at 60 cm, air temperature at 110 cm, and radiant temperature asymmetry with façade) were statistically significantly correlated to user satisfaction. When the six factors are controlled, user satisfaction can increase by 38% ($p<0.001$), which can reach 83% of thermal acceptability.

Air temperature: Ensuring that the air temperature at 2ft (60 cm) and 4ft (110 cm) from the floor is above 76.5°F (24.7°C) in summer could increase user satisfaction by 0.73 on a 7-point scale ($p<0.05$). During the heating and swing seasons, most of the measured temperatures were within the ASHRAE 55 thermal comfort range which is between 68 °F (20°C) and 78°F (25.6°C). However, during the cooling season, 36% of measured temperatures were below the comfort range and resulted in 58% dissatisfaction in the user thermal survey (Figure 2). The majority of the temperatures for the dissatisfied workstations were around 73.3 °F (22.9°C), and the satisfied group's temperatures were around 76.5°F (24.7°C). The difference is statistically significant ($p< 0.05$). Based on this analysis, in the summer people are more satisfied at a 76.5°F (24.7°C) air temperature than at 73.3 °F (22.9°C).

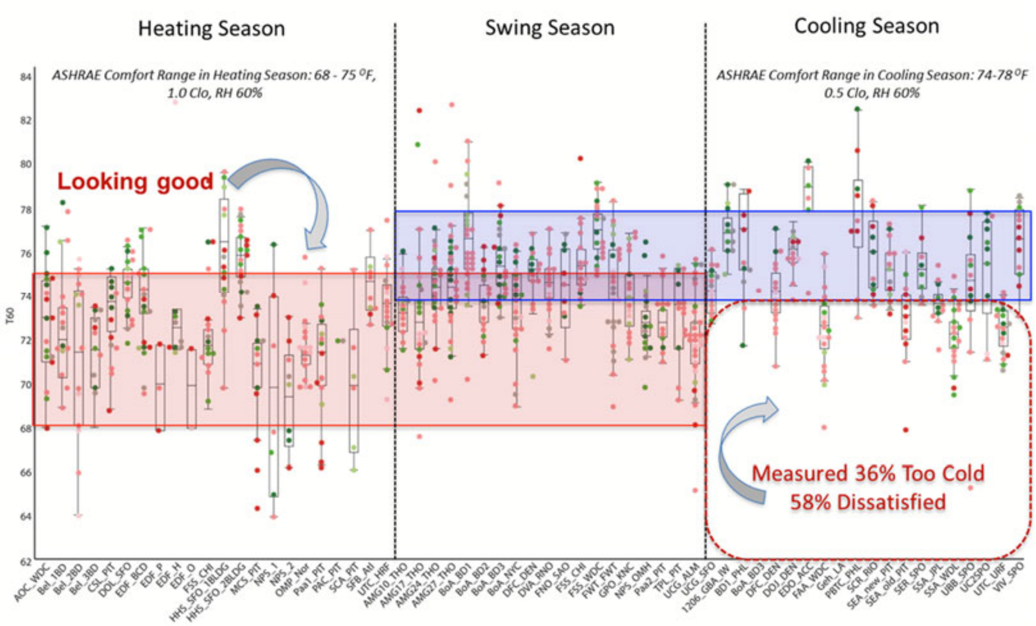

Figure 2 Air temperature at 60 cm (2 ft) from the floor (n=1,282)

Size of Zone: Temperature satisfaction increased as the thermal zone decreased by size, and as fewer people shared a single thermostat. Providing individual thermal zones had the second largest impact and increased user satisfaction by 1.06 points on a 7-point scale (n=1,155, b=64, p<0.001). The distribution in size of zone for 1,155 questionnaire respondents in 64 buildings showed that 69% of the offices were controlled by 15 people or less (10-15 people per thermostat = 33% and 5-10 people per thermostat = 36%). About 19% of workstations were controlled by less than five people (individual control = 5% and 2-5 people = 14%) and 13% of offices had one thermostat shared by 15-25 people. The results show that temperature satisfaction did increase as the thermal zone decreased by size, as fewer people shared a single thermostat in both heating and cooling seasons. On average, 80% of occupants were satisfied with an individual thermal zone, while only 20% of occupants were satisfied when 15-25 people shared one thermostat (n=737, b=44, P<0.0001) as shown in Figure 3. The disparity was especially significant for women during the cooling season with the highest thermal dissatisfaction in large zone areas (with colder temperatures and seasonal clothing). During the cooling season, when 15-25 people shared one thermostat, only 7% of female occupants were satisfied with the air temperature, while the workstations with the individual thermostat showed 64% satisfaction (n=422, b=22, p<0.001).

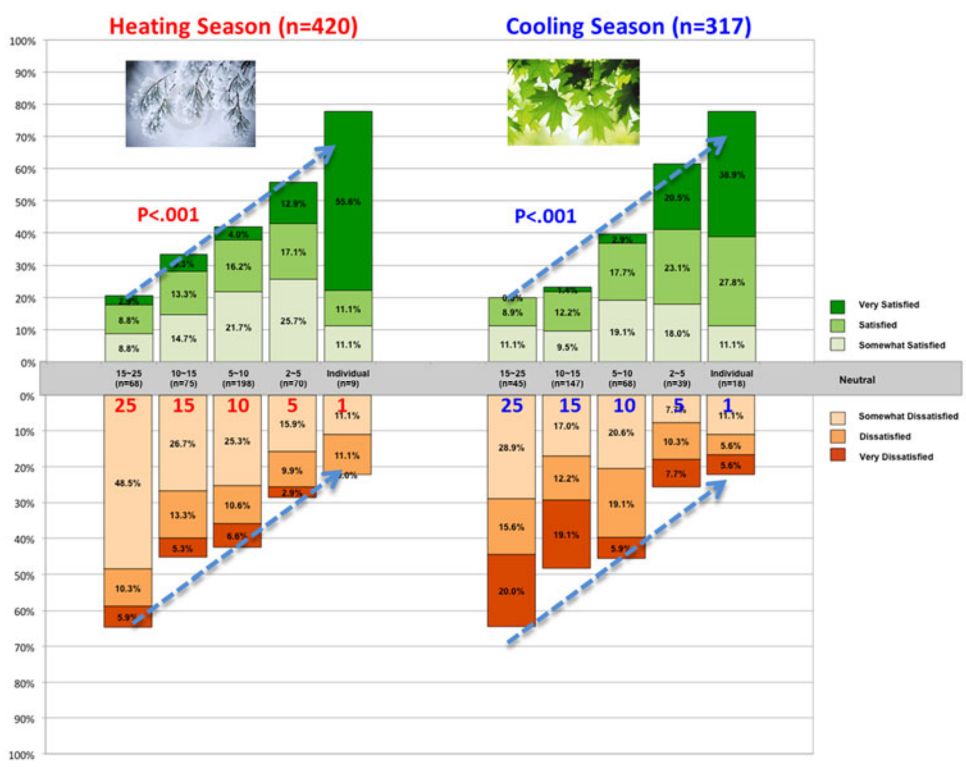

Figure 3 Temperature satisfactions by Size of Zone (Heating and Cooling Season, 44 Buildings, n=737). The smaller the thermal zone (fewer people sharing a thermostat), the greater the satisfaction with air temperature in the workstation.

Window Quality: The higher the window quality (tightness and number of panes), the greater the satisfaction with air temperature in the workstation. Given the NEAT database of 1,155 workstations in 64 buildings, window quality is the most critical factor for occupant satisfaction, and increased occupant satisfaction by 1.48 points on a 7-point scale (n=1,155, b=64, $p<0.001$). The results show that about 65% of workstations had double pane or moderate tight windows and 15% had single pane, leaky windows. During the heating and cooling seasons, 67% of occupants in perimeter offices reported thermal dissatisfaction in the workstations with leaky, single pane windows, and only 15% of occupants were satisfied with their air temperature. However, in workspaces with tight (triple or double panes) windows, on average, 65% of occupants in the perimeter office were satisfied with their air temperature (n=583, b=44, $p<0.001$).

Level of Temperature Control: Installing controllable thermostats increased user satisfaction by 1.32 points on a 7-point scale ($p<0.01$). The distribution in level of temperature control for 1,004 questionnaire respondents in 64 buildings showed that 65% of the offices were each controlled by a hidden thermostat, while 17% had a visible but locked thermostat, and 18% of the offices had a controllable thermostat. Occupants with access to controllable thermostats had higher satisfaction (62%), while locked but visible thermostats yielded worse satisfaction (22%) than hidden thermostats (36%). Locked but visible thermostats were worse than hidden thermostats (n=1,004, b=64, $p<0.01$) (Figure 4).

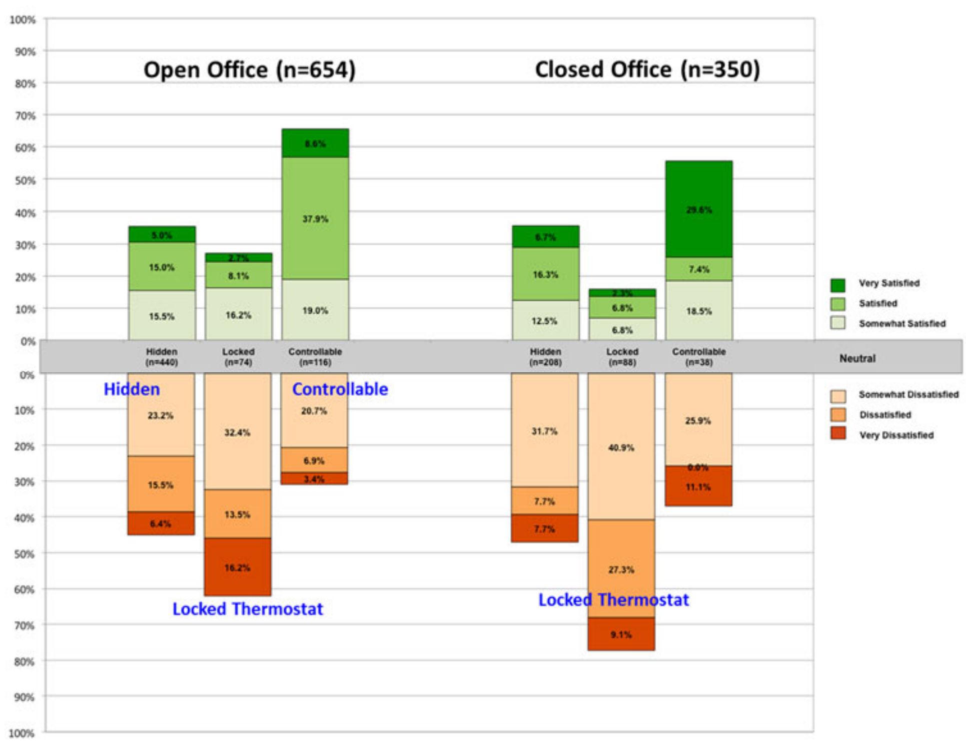

Figure 4 Temperature satisfaction by Level of Control (Open and Closed Office, n=1,004). Individuals with hidden or locked thermostats will be 20-40 % less satisfied with air temperature in their work area ($p<0.01$), locked but visible thermostats are worse than hidden thermostats.

Radiant temperature asymmetry with façade: Ensuring that the temperature asymmetry between exterior and interior walls is less than 7.01 °F increased user satisfaction by 0.73 points in perimeter offices (n=692, b=64, $p<0.001$). There is a significant correlation between radiant temperature asymmetry between exterior and interior walls and user satisfaction in perimeter offices ($p< 0.0001$), but the relationship is not relevant in core offices ($p= 0.08$).

3.2. Air Quality

Given the NEAT database of 1,197 workstations in 64 buildings, overall, 65 % of occupants responded "satisfied" or "neutral" and 35% of occupants reported "dissatisfied" with their thermal conditions. The average air satisfaction level was 4.1, which is at 'neutral' with their air satisfaction on a 7-point scale. Six factors are significantly important in air satisfaction.

CO_2 level: Given the measured CO_2 concentration from 1,282 workstations in 64 buildings, occupant satisfaction with overall air quality is strongly linked to CO_2 levels, with significant shifts to satisfaction when CO_2 level is less than 600 ppm (n=1,282, b=64, $p < 0.05$) (Figure 5). The average measured CO_2 level was 670 ppm. When the CO_2 concentration is less than 600 ppm, occupant satisfaction increases 1.5 points on a 7-point scale

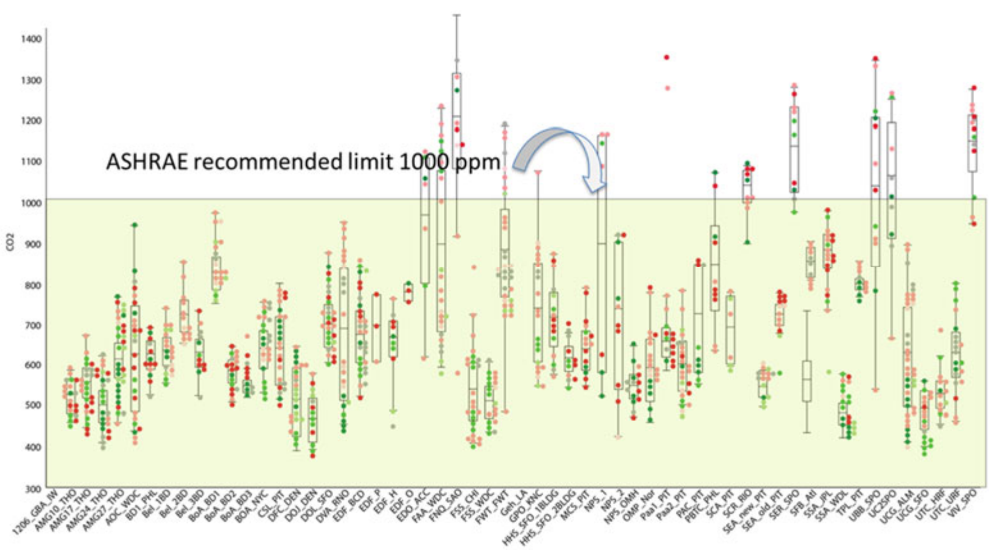

Figure 5 CO_2 measurements (n=1,282, mean= 670 ppm) with ASHRAE recommendation

Operable window: Access to an operable window can increase user satisfaction for air quality. The distribution for 590 questionnaire respondents in parameter workstations showed that only 24% of occupants can open a window and the other 76% of the occupant cannot. Out of all occupants, 66% would be more satisfied with operable windows (n=590. b=64, $p<0.01$). On average, occupants with an operable window have 30% higher user satisfaction than those without an operable window.

Dedicated exhausts: Satisfaction for air quality could increase with a space with all dedicated exhaust for kitchens and copy areas. Among 665 respondents, 41% of workstations didn't have dedicated spaces or exhausts for kitchen and copy areas, instead these areas were located in or around aisles or empty workstations. 46% of surveyed workstations had some dedicated areas for kitchen and copiers, and only 13% had all dedicated spaces with exhausts. Occupant satisfaction with overall air quality would be strongly linked to the design of dedicated copy and kitchen areas with exhausts, instead of distributed appliances throughout the open plan. There was a statistical difference with all dedicated exhausts in open-plan workstations: on average, all dedicated spaces with exhausts had higher satisfaction (70%), while workstations which didn't have dedicated spaces or exhausts and copy and kitchen areas near aisles or empty workstations showed lower temperature satisfaction (41%) (n=717, b=64, p<0.001).

Return air density: Satisfaction for air quality increased as the return air density per person decreased. The distribution in size of zone for 1,036 questionnaire respondents in 64 buildings showed that 62% of the offices were controlled by 5-10 people per one return air unit. About 24% of workstations were controlled by 1 person per return air unit (24%). The occupants who have individual return air unit showed 65% satisfaction while 1 per 25 return air density showed 25% user satisfaction. Providing one return air unit per person increased user satisfaction by 1.26 points on a 7-point scale (n=1,036, b=64, p<0.001).

Window quality: The higher the window quality (tightness and panes), the greater the satisfaction of overall air quality and air movement in the workstation. Given the NEAT database of 717 workstations in 64 buildings, window quality increased occupant satisfaction by 0.51 points on a 7-point scale user satisfaction survey (n=1,717, b=64, p<0.001). The result showed that about 69% of workstations had double pane or moderate tight windows and 13% had single pane, leaky windows. The occupants who have tight windows showed on average 25% higher user satisfaction for air quality (n=717, b=64, p<0.001).

Partition height: The lower the partition height, the greater the satisfaction of overall air quality and air movement. Given the NEAT database of 500 workstations in open-plan workstations, low or medium partition height could increase occupant satisfaction by 0.4 points on a 7-point scale as compared to a high partition height (n=500, b=64, p<0.01). The result showed that about 46% of workstations had low or medium height partitions and 54% had high partitions. The occupants who have low or medium partitions showed on average 23% higher user satisfaction for air quality (n=717, b=64, p<0.001).

3.3 Visual Quality

Given the NEAT database of 1,038 workstations in 64 buildings, overall, 79% of occupants responded "satisfied" or "neutral" and 21% of occupants reported "dissatisfied" with their thermal conditions. The average visual satisfaction level is 4.8, which falls between 'neutral' and 'somewhat satisfied' with their satisfaction on a 7-point scale (n=1,038, b=64, p<0.001).

Seated View: Among 1,232 workstations in 64 buildings in the NEAT database, 41% had a seated view while 59% did not have a view to the outside. On average, 70% of occupants who have a seated view showed satisfaction for visual quality. Providing a seated view to occupants increased user satisfaction 0.76 points on a 7-point scale survey (n=1,038, b=64, p<0.05). User satisfaction increased by 22% with a seated view.

Ceiling Lens Type: Visual satisfaction increased with an indirect ceiling lens type in the workstations with no seated views. On average, workstations with the indirect lens type had higher satisfaction (61%) while the prismatic celling lens type showed the lowest user satisfaction (32%). Upgrading to the indirect lens type increased user satisfaction by 1.32 points on a 7-point scale survey.

Ceiling Light Fixture: Given the distribution in ceiling light fixtures for 980 questionnaire respondents in 64 buildings, 64% of the offices had 2x4 or 1x4 type ceiling light fixtures. About 22% of workstations had indirect celling light, and 5% of offices had indirect light fixtures with task lights. The occupants who had indirect ceiling lights with their own task lights were highly satisfied with their overall visual quality, on average, 80% of users were satisfied while about 20% of occupants were dissatisfied with 2x2 ceiling light fixtures.

Shading Type: Given the distribution in shading type for 995 questionnaire respondents in 64 buildings, 82% of the offices were controlled by horizontal blinds (45%, n=452) and vertical blinds (37%, n=370). About 5% of workstations had both external and internal shading devices in their work areas. Among 451 respondents who have seated views, the occupants who have both external and internal shading devices showed highest satisfaction, 62% were satisfied with their overall lighting.

Light level on work surface: Given the measured illuminance levels from 1,236 workstations in 64 buildings, the average workstation light level (as is conditions) is 617 lux. 61% of the 1,236 workstations are above the IESNA recommended level of 500 lux. When the task lights are off, the average illuminance level is 460 lux and still 42% of work stations were over the recommended level.

3.4 Acoustic Quality

On average, people are somewhat dissatisfied with their acoustic conditions, (3.75 points on a 7-point user satisfaction scale). Four factors are significantly important to acoustic satisfaction.

Size of Workstation: Acoustic satisfaction increased as the workstation size increased. Given the distribution in size of workstation for 570 questionnaire respondents in 64 buildings, about 75% of workstations in open-plan office are less than 64 sq. ft, and 25% are bigger than 64 sq. ft. Workstation sizeis positively correlated with both background noise satisfaction and frequency of distraction ($p<0.05$, n= 571). On average, 63% of occupants were satisfied when the size of the workstation is bigger than 100 sq. ft.

Distributed Noise Level: Among 485 respondents, 35% of workstations had 10-40% of distributed noise level in their work area and about 14% of workstations showed less than 2% of distributed noise levels in their work area. Acoustic satisfaction increased as distributed noise level decreased. The relation is positively correlated with both background noise and frequency of distribution ($p<0.001$, n= 485).

Partition Sides: Given the distribution in partition sides for 559 questionnaire respondents in the open plan offices in 64 buildings, 37% of the workstations were surrounded by 2-3 sides with partitions and 27% had only 1 side with a partition. Acoustic satisfaction increased with more partition sides in the open-plan office. On average, workstations with 3.5 to 4 partition sides had higher satisfaction (56%), while 2-3 sides (48%) and no partition (33%) showed lower acoustic satisfaction in both background noise level ($p< 0.05$) and frequency of distraction in their work area (n=559, b=64, $p<0.001$).

Partition Height: Among 493 respondents in open plan offices, 55% of workstations had low or medium height partitions and 45% of occupants had high partitions. On average, workstations with high partitions showed 8% higher satisfaction than those with low or medium partitions.

Finally, Table 1illustrate the technical attributes of building systems that significantly impacted user satisfaction on thermal, air, visual and acoustic quality and thresholds derived from given US average buildings. Key IEQ indices can be defined using occupant survey responses and the detailed indices and questions. For example, asking occupants, "are you satisfied with your temperature in your work area?" can inform whether room air temperature is within the comfort range or not. Also, occupant satisfaction survey response can redefine user comfort thresholds. Given our dataset, using 1,601 workstation's IEQ measurements and user satisfaction survey responses from 64 buildings, IEQ comfort thresholds for highest building occupant satisfaction were redefined as shown in Table 2.

Table 1 Measured IEQ and Technical attributes of building systems which significantly impacted user satisfaction

IEQ Criteria	*Measured IEQ*	*Technical attributes of building systems*	*User Satisfaction Questions*
Thermal Quality	• Air temperature at 60cm from the floor • Air temperature at 110cm from the floor • Radiant temperature asymmetry between exterior and interior wall	• Size of Zone • Window Quality • Level of Control	Q. Are you satisfied with your temperature in your work area
Air Quality	• CO_2 level	• Operable window • Dedicated exhausts • Return air density • Window quality	Q. Overall air quality in your work area
Visual Quality	• Luminance ratio • Illuminance level	• Seated View • Ceiling Lens Type • Ceiling Light Fixture • Shading Type	Q. Overall quality of lighting in your work area Q. Light for paper-based work
Acoustic Quality	• Background noise level	• Size of workstation • Distributed Noise • Partition Sides • Partition Height	Q. Background noise in your work area Q. Frequency of distraction from others

Table 2 Redefined thresholds for user comfort derived from given US average buildings

IEQ Criteria	*IEQ measurements*	*Thresholds for highest satisfaction (given US average bldgs.)*		*Standards*
Thermal Quality	Air temp at 60 cm in heating season	72.7 - 73.8 °F (Female)	72.0 - 73.1 °F (Male)	68 - 75°F (ASHRAE 55)
	Air temp at 60 cm in cooling season	76.1 - 77.0 °F (Female)	75.7 - 76.5 °F (Male)	74 - 78 °F (ASHRAE 55)
	Horizontal Radiant temperature Asymmetry	< 3.18 °F (Female)	< 4.01 °F (Male)	< 18 °F (ASHRAE 55)

IEQ Criteria	IEQ measurements	Thresholds for highest satisfaction (given US average bldgs.)	Standards
		< 7.01 °F	< 18 °F (ASHRAE 55)
Air Quality	Carbon dioxide	< 615 ppm	< 1100 ppm (ASHRAE 62.1)
Visual Quality	Illuminance on monitor	290 lux	500 lux (IESNA 2011)
	Illuminance on keyboard	400 lux	500 lux (IESNA 2011)
	Illuminance on work surface	400 lux	500 lux (IESNA 2011)

4. Research limitation and Conclusion

There are some limitations of this research. First, the conclusions were based on field measurement data as opposed to controlled experiments derived from an existing mixed- quality building stock. Second, the data are collected from NEAT short-term spot measurements in one season per building. Third, data collection for technical attributes of building systems was dependent on interpretations of experts in the field. For example, sometimes, diffuser alignments were recorded by the perception of on-site building performance measurement professionals. Not always from the building system drawings.

This research revealed an integrated approach to POE with indoor environmental quality measurements by leveraging occupants as sensors to quickly capture IEQ conditions in a work environment. This approach identified critical factors in the physical environment that impacts building occupant comfort and satisfaction. This approach provides practical IEQ assessment methods and procedures centered on the occupants' perspective. The ultimate outcome of this research can contribute to explore 1) correlations between occupant perception and measured data, 2) a refined survey method to assess building IEQ capable of robust prediction of building performance, and 3) metrics and guidelines for IEQ standards that capture new IEQ thresholds that impact building occupants' satisfaction.

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