Analyses of IEQ and User Satisfaction in 20 Office Buildings
Significant findings to impact future design standards and guidelines

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ABSTRACT: The aims of this study are to present significant findings from building post occupancy evaluations with environmental measurements and occupant surveys, and to improve environmental design standards and guidelines for commercial office buildings. In partnership with the General Services Administration (GSA), the study was conducted on 38 floors in 20 office buildings in the U.S. Indoor environmental conditions of air quality, thermal quality and lighting quality were measured and user satisfactions with environmental qualities were also surveyed. These objective and subjective data were used to do correlational analysis. The study results provide evidences to modify office environmental design guideline to improve physiological and environmental benefits.

INTRODUCTION
Indoor environmental quality (IEQ) is a significant variable affecting occupant health, productivity as well as organization success [1]. Therefore, it is critical to ensure occupant comfort and satisfaction for each component of indoor environmental quality: thermal, air, light/visual, spatial and acoustic qualities. However, most standards and guidelines are based on empirical studies and laboratory experimentation setting with environmental conditions that may vary significantly from actual indoor environments with more complex mechanical, lighting and spatial systems configurations than those assumed for the controlled experiments. Moreover, the nature of work of building occupants has changed significantly as our industry becomes more computerized, and the thermal, air, visual and acoustics environments are extensively affected by the IT tasks. In addition, real estate forces have caused buildings to be deeper limiting the occupants' access to nature.

For these reasons, the current standards and guidelines may not adequately address the rapidly changing building environmental conditions, resulting in an increase in occupant dissatisfaction with indoor environmental factors and causing unnecessary energy use.

In partnership with the General Services Administration (GSA), the Center for Building Performance and Diagnostics research team at Carnegie Mellon has performed post occupancy evaluation field studies of 20 commercial office buildings throughout the U.S. Based on the collected data of indoor environmental qualities, expect reviews of the Technical Attributes of Building Systems (TABS), user satisfaction questions (COPE) [2], these field study support future design standard and guideline recommendations for improving.

METHODS
The research team, Center for Building Performance and Diagnostics at Carnegie Mellon University in the U.S. has conducted numerous post occupancy evaluation field studies of 20 commercial office buildings from 2003 to the present. The studies performed environmental measurements of air quality, thermal quality visual/lighting quality and acoustics quality for objective data acquisition in 402 workstations and a survey of occupant satisfaction of each IEQ component for subjective data acquisition. The physical attributes of the surveyed workstations including physical locations and workstation types, system specifications, and human factors such as gender and age. The analyzed dataset is from 402 sampled workstations with 212 females and 190 males, on 38 floors in 20 office buildings across the U.S.

An environmental quality instrument cart developed by the research team and hand-held sensors to measure the full suite of locations: air temperatures at 1.1m, 0.6m and 0.1m levels, radiant temperatures, relative humidity, illuminance on workstation surface, computer keyboard and monitor, contrast ratio between computer screen and its background, unified glare rating, air quality levels including CO_2, CO, VOC and particulates, air velocity, background noise level, and acoustic sound transmission (privacy). The on-site occupant survey supporting simultaneous mapping of perception to measured performance included 25 questions on IEQ satisfaction developed by National Research Council Canada with a 7 point scale for scoring (Table 1).

Table 1: Environmental satisfaction level used for the building occupant survey.

Score	Satisfaction level
1	Very dissatisfied
2	Dissatisfied
3	Slightly dissatisfied
4	Neutral
5	Slightly satisfied
6	Satisfied
7	Very satisfied

This study incorporates two-sample T-tests and correlational analyses to study correlations between occupants' satisfaction and objective measurements of environmental quality.

DATA ANALYSIS

On average, most measured environmental conditions are within the conventional standard guidelines for each IEQ component list. However, the surveyed data from the sampled building occupants show significant variations in satisfaction irrespective of the recommended comfort standards. The most significant findings in each environmental component including thermal, lighting and air qualities, follows:

Thermal Quality *Occupants in perimeter zones reported higher thermal satisfaction than in interior zones despite similar thermal environments.*

To investigate the thermal satisfaction differences between occupants in perimeter zones and interior zones, the collected thermal comfort survey data were grouped by distance from the window wall: perimeter zones (those workstations within 10 feet from the external wall or window), and interior zones (occupants seated more than 10 feet from the window walls).

Given data across all seasons, the occupants in perimeter zone reported higher satisfaction with temperature than those in interior zones with a high statistical significance (p=0.003). As Figure 1 illustrates, the average satisfaction in perimeter is 3.97 on a scale (Table 1) while the interior is 3.43 with statistical significance of p=0.003.

Further analysis was undertaken to assess user perception and measured conditions by season as reflected in ASHRAE-55 standards [3] in response to changing Clo-values. The data are divided into cooling and heating seasons based on mechanical system operating status. In cooling season, the occupants reported predominantly neutral in thermal satisfaction (3.89 on a scale (Table 1)) in perimeter workstations versus 'slight dissatisfied' (2.96) in interior workstations, statistically significant with p = 0.003 (Figure 2).

Figure 1: Confidence Internal comparison of occupant thermal satisfaction level between perimeter and interior zones with all the seasons data (average 3.43(Interior) vs. 3.97 (Perimeter), p=0.003).

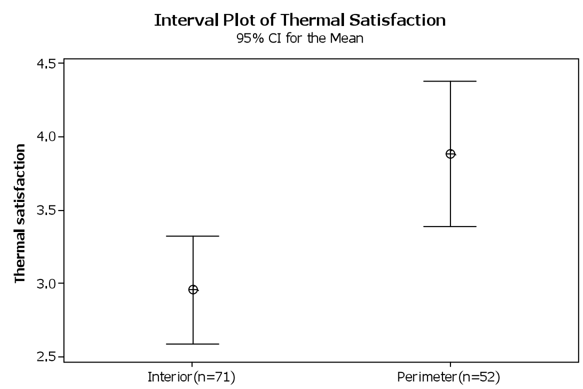

Figure 2: Confidence Interval comparison of occupant thermal satisfaction level between perimeter and interior zones with cooling season data (average 2.96 (Interior) vs. 3.89 (Perimeter), p=0.003).

Assessment of the heating season data yields a similar result. The average satisfaction level of the occupants in perimeter workstations is 4.00, and occupants in interior workstations record an average satisfaction level of 3.48 with statistical significance of p=0.04 (Table 3).

As illustrated in Figure 1, 2 and 3, occupant thermal satisfaction in perimeter workstations are 15 to 30% greater even under similar thermal environments. Mechanical systems controls are set to provide uniform environmental conditions in both perimeter and interior zones, and predominantly achieve uniform levels. However, occupant satisfaction with thermal conditions is slightly greater in perimeter workstations. This may be due to local HVAC unit controls through many of additional controls in perimeter zones, such as blinds, operable windows, and functioning perimeter temperature controllers or even accessible vents to cover their micro-climate and to enhance their thermal satisfaction. Therefore, designing office layouts to maximize the perimeter workstations with accessible micro-climate controllers would improve employee satisfaction with thermal comfort.

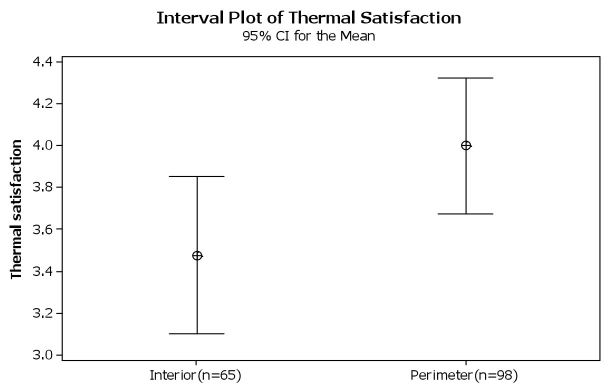

Figure 3: Confidence Internal comparison of occupant thermal satisfaction level between perimeter and interior zones with heating season data (average 3.48 (Interior) vs. 4.00 (Perimeter), p=0.04).

Different genders reported different thermal satisfaction in similar thermal environments. Females were more sensitive to lower temperatures than males, and reported lower satisfaction during cooling season.

In the investigated buildings, the collected temperatures are distributed from 20.5 ºC to 28.0 ºC in cooling season. The average temperature is 23.29 ºC with the standard deviation of 1.509. 48% of the sampled workstations show lower temperatures than ASHRAE-55 standards for cooling season. To compare the thermal satisfactions by gender, the cooling season data are divided into each gender group. According to the result of the two-sample T-test, there is no statistically significant difference in thermal conditions for males and females with p=0.62 (Figure 4). The average temperatures are 23.34 ºC and 23.22 ºC in the male and female groups respectively.

However, female occupants were less comfortable in the cooling season with statistical significance of p=0.000. The average satisfaction level of female occupants is 2.76 while the level of the male group is 3.87 on a scale (Figure 5).

Therefore, this finding suggests that if current thermal comfort guidelines were modified to consider the thermal satisfaction difference by gender or individual thermal comfort became a design standard, it would contribute to improved thermal satisfaction overall.

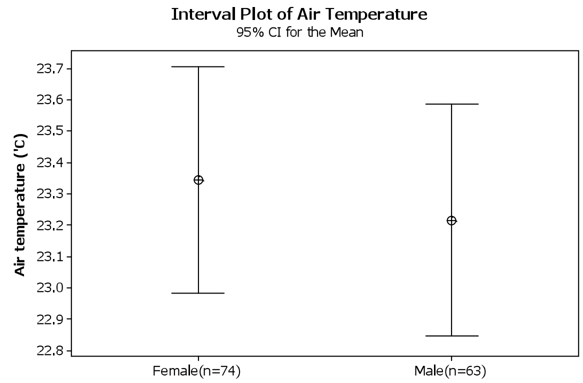

Figure 4: Thermal conditions in female and male groups (average 23.34ºC (female) vs. 23.22ºC (male), p=0.62).

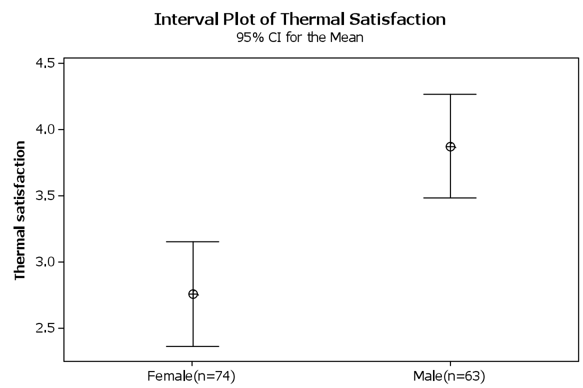

Figure 5: Comparison of Confidence Interval of thermal satisfaction between female and male groups (average 2.76 on a scale (female) vs. 3.87 (male), p=0.000).

Lighting Quality *Satisfaction with lighting conditions increase when lighting levels decrease to levels substantially lower than the current minimum standards.*

In one field study of 200 workstations, pre and post analysis of objective and subjective lighting quality were conducted. Spot measurements were collected on the surface of the monitor, keyboard and primary worksurface from 17 and 27 workstations in the pre and post-renovation conditions respectively.

The current IESNA standards [5] suggest minimum illuminance levels depending on work types and critical spots of a workstation. Thus, lighting levels are conventionally designed with the idea of 'higher illuminance would be always better' based on the current standards. However, as today's most office occupants are dedicated to computer-based tasks, excessive lighting may cause visual discomfort due to glare and unnecessary reflection on computer screen.

As Figure 6 shows, overall lighting levels of the post-condition are significantly lower than the pre-condition. The illuminance of monitor, keyboard and worksurface in the pre-condition is higher than the post-condition. In the pre-condition, illuminance level at the worksurface shows an average at 847 lux, keyboard at 652 lux, and monitor at 480 lux. On the other hand, worksurface of post-condition shows an average at 419 lux, keyboard at 313 lux, and monitor at 134 lux.

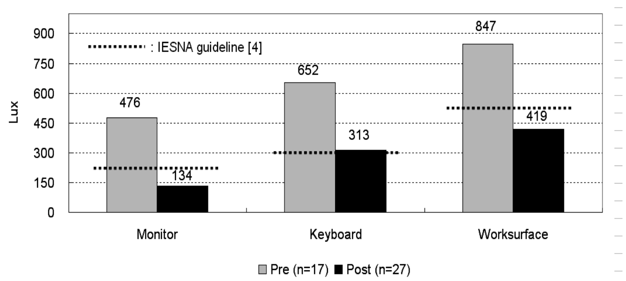

Figure 6: Comparison of illuminance between Pre and Post conditions and IESNA guideline (all comparison sets are statistically significant with p=0.000).

However, there is larger percentage of respondents in the post-condition reporting their satisfaction with lighting quality for computer-based and paper-based works by 20% difference in spite of their lower lighting levels compared to the pre-condition (Figure 7 and 8). According to the survey about daily task types, occupants spend on average 80% of their working hours on computer-based tasks. It implies that lower lighting levels are much appropriate for computer-based tasks.

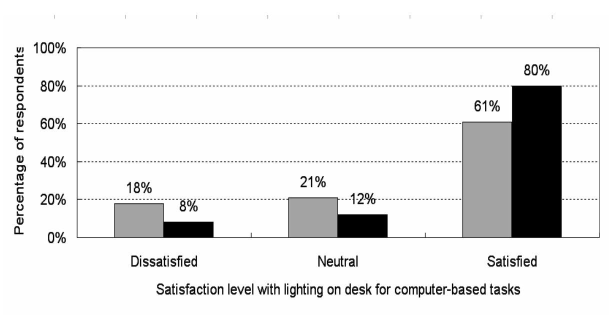

Figure 7: Comparison of satisfaction level with lighting on desk for computer-based tasks between pre- and post-conditions.

One cross-sectional analysis results also supports the significance of lighting quality for computer-based tasks. As Figure 8 shows, user satisfactions are higher with lower lighting levels for computer-based work, but reversed for paper-based work. When the lighting level on worksurface is 500 lux or less, the satisfaction levels with glare on screen is between 'neutral' and 'slightly satisfied', but it is drastically reduced when the lighting level is over 500 lux. On the other hand, the satisfactions for paper-based work increase as the lighting level rises.

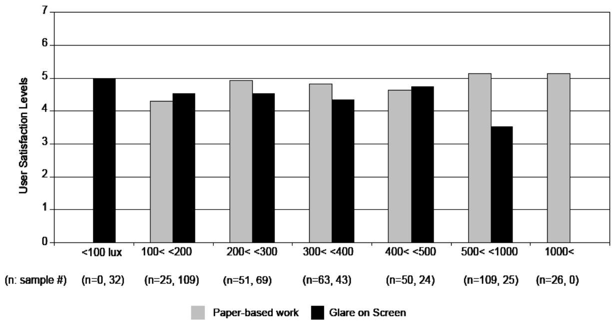

Figure 8: Changing patterns of user satisfactions with lighting level on workstation surface for paper-based work and glare on computer monitor screen (The satisfaction scores follow the scale in Table 1).

These findings show the need of upper limits of lighting levels in the standards in order to comply with the user visual properties for a task type. Thus, rather than suggesting only minimum lighting levels for office work environment, proper lighting ranges by specific task types and device features would be effective to generate an optimal lighting environment for enhancing user satisfaction. Also, if office lighting design guidelines could include providing flexible task lights, the satisfaction with lighting quality would be improved irrespective of task types.

Air Quality *Proper air velocity levels led higher satisfaction rates of air movement and overall air quality than no air movement condition while the current standards suggest only an upper limit of air speed with considering thermal comfort condition.*

Air velocity and particulate level were measured in the sampled workstations. According to conventional thermal comfort theory [5], air velocity is treated as one of environmental variables to decrease or increase thermal comfort perception depending on seasons. According to the theory, air speed can generate cooler condition in cooling season while it can get worse the comfort condition in heating season.

The on-site investigation and the survey data show there is negative correlation between air particulate levels, and the satisfactions of air quality and air movement. The sampled workstations where the collected air velocity data are within the ASHRAE guideline (: ≤ 40 ft / minute) show that proper air speed seems to lead lower air particulate levels, and resultantly higher satisfactions of air quality and air movement than no-air movement condition. Such air draft may lead a certain level of air circulation to provide perception of relatively fresh air and to prevent the occupants from feeling stuffy.

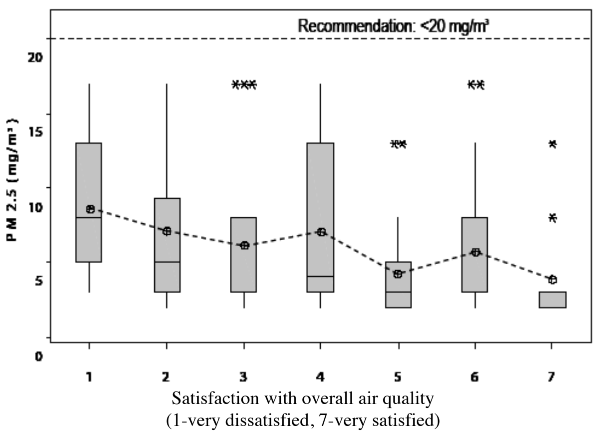

Figure 9: Correlation between overall air quality satisfaction and particulate levels in workstations (n=133, R=-0.239, p=0.006)

As Figure 9 shows, overall air quality satisfaction increases with lower small particulate levels in workstations. And, air movement satisfaction increases with lower small particulate levels in workstations (Figure 10). It shows negative relation with R=-0.255 and statistical significance (p=0.003).

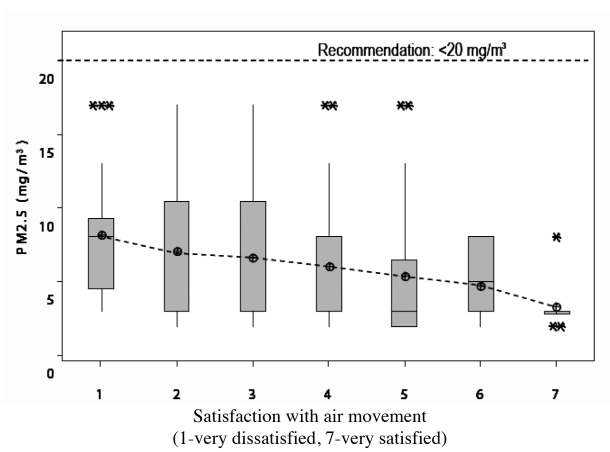

Figure 10: Correlation between air movement satisfaction and particulate levels in workstations (n=133, R=-0.255, p=0.003)

Based on these findings, we can deduce that a certain level of air movement in workstations could reduce the particulate levels contributing indoor air quality rate. Thus, if the current standards suggested a proper level of air speed as a lower limit which might not disturb thermal comfort conditions, it would contribute to air quality satisfaction overall.

CONCLUSION

This field study with the on-site measurement and survey provides supportive ideas for environmental standards and design guidelines for office environments which could satisfy the current office task types, physiological and IEQ demands. For thermal quality, workstation location seems to be an important role to occupant thermal satisfaction rates. Also, physiological property by gender could influence on the thermal comfort conditions.

Office task type is a major variable to have an effect on lighting quality satisfaction. As the required lighting environments for computer-based tasks with electric monitor screen devices are different from the conditions for conventional paper-based tasks. The on-site investigation suggests a different approach to air movement of office buildings. Air movement seems to significantly affect occupant air quality satisfactions with reducing particulate levels.

As this study was performed in 20 government office buildings, the degrees of these findings may vary depending on individual building environments. However, the study is still meaningful in terms of providing evidences to be able to modify or create design guidelines and environmental standards based on them in order to enhance physiological and environmental benefits. Thus, the study may require additional investigation with more number of samples to improve robustness of the findings and to suggest more detailed ideas for improving guidelines and standards.

ACKNOWLEDGEMENTS. This study was made possible by funding support from the U.S. General Services Administrations. The authors thank Kevin Powell, Kevin Kampschroer, Sam Hunter, and David Bibb for their valuable comments and to PhD and Master Students of Center for Building Performance and Diagnostics at Carnegie Mellon University for their data acquisition and recording. The authors would also like to express the gratitude to Viraj Svastava, Maffee Wen and Yuchang Hu for their valuable help.

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