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Publisher's version / Version de l'éditeur:

The Future of Praxis: Applied Research as a Bridge Between Theory and Practice: Proceedings of the ARCC 2019 International Conference, pp. 673-682, 2019-05-29

Evaluating the in-situ effectiveness of indoor environment guidelines on occupant satisfaction

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ABSTRACT: Post occupancy evaluation (POE) studies typically use a combination of occupant questionnaires and physical measurements of various aspects of the indoor environment to assess building performance. These physical measurements are often compared against published reference limits to evaluate compliance and satisfactory performance. This study investigates whether indoor environment conditions compatible with published indoor environment quality (IEQ) standards and guidelines are predictive of occupant satisfaction. Data used in this study were collected as part of two large building evaluation field studies conducted in the past eight years. Occupant questionnaire and physical measurement data from 11 office buildings across North America were used (N=194). Inputs for the analyses were demographic factors and workstation characteristics, as well as aspects of the measured physical indoor environment. Outcome variables were various measures of environmental satisfaction (i.e. lighting, acoustics/privacy, and ventilation/temperature). The results of this study suggest that occupants had higher satisfaction with lighting when measured desktop illuminance levels were within IESNA RP-1-12 (2012) recommendations. Measured sound levels and thermal conditions within reference limits did not correlate to higher occupant satisfaction in their respective categories.

KEYWORDS: Indoor environment quality, post occupancy evaluation, lighting, acoustics, thermal comfort

INTRODUCTION

People in developed economies typically spend 90% of their lives indoors (Klepeis et al. 2001; Leech et al. 2002), and rising concern for occupant well-being mean that indoor environment quality (IEQ) and occupant comfort are receiving increasing attention in both research and industry. It has been well established in literature that aspects of the physical workspace have an effect on job satisfaction, stress levels, and health (Klitzman and Stellman 1989; Pejtersen et al. 2006). A well-conditioned indoor space plays a crucial role in achieving higher levels of organizational productivity and well-being (World Green Building Council 2014). In terms of economic importance, studies have demonstrated the significant financial benefits of improved IEQ (Fisk, Black, and Brunner 2011).

A commonly applied method of evaluating in-situ performance of a building is through post-occupant evaluations (POEs). POEs are a process that involves evaluating buildings in a systematic manner after they have been built and occupied for some time (Preiser and Vischer 2005). There are many existing POE field studies evaluating aspects of the physical workspace and occupant satisfaction using questionnaires or physical measurements, or both. Numerous studies have shown the importance of various demographic factors and physical aspects of the workspace on occupant satisfaction. Previous studies have consistently shown significant differences in terms of environmental satisfaction across sexes and age groups (e.g. Kim, de Dear, Cândido, Zhang, & Arens, 2013; Leder, Newsham, Veitch, Mancini, & Charles, 2016; Newsham, Veitch, & Charles, 2008). Others have found significant relationships between workstation enclosure (i.e. private versus open-plan workstations) and occupant satisfaction (Kim and de Dear 2013; Leder et al. 2016). The beneficial effects of windows in the workstation are also well established in literature (Frontczak et al. 2012; Galasiu and Veitch 2006; Yildirim, Akalin-Baskaya, and Celebi 2007).

With regards to physical IEQ, many field studies have measured indoor environment conditions and compared them to recommendations in various published standards and guidelines (e.g. ASHRAE 55). For instance, in a POE study of 52 office buildings, Pei et al. (2015) compared thermal and lighting measurements against prevailing standards but performed no further validation of their effects on satisfaction. Other researchers (e.g. Ali, Chua, and Lim 2015; Kwon, Chun, and Kwak 2011; Liang et al. 2014) used similar comparisons of indoor environment measurements against relevant standards as an indication of acceptable performance. Although these published standards and their recommended IEQ thresholds are based on consensus derived from studies of human response to physical conditions, the studies were primarily conducted in controlled laboratory conditions and each study focused on a single aspect of the indoor environment. The analysis in this paper examines some of these published physical IEQ guidelines and recommendations for their effectiveness in achieving occupant satisfaction in a commercial office setting. The results will provide additional insight on the validity of these recommendations, and the potential for future revision of recommendations, and of POE protocols.

2.0 METHODOLOGY

2.1 Data Source

The analysis in this paper uses existing field data from two studies that gathered data from occupied offices in combination with questionnaire responses from the occupants of these workspaces. The research protocols were approved by the NRC Research Ethics Board.

The first study involved data collected from public and private sector employees in 12 conventional buildings and 12 green buildings across Canada and the northern United States. The questionnaires were distributed electronically online to the participants, while a representative sample of the workspaces were measured using portable equipment that provided a detailed snapshot of the indoor environment in an individual office space over a 10 to 15-minute period. Physical indoor environmental factors such as sound level, temperature, air speed, relative humidity, concentrations of various air pollutants, and desktop illuminance were measured. The occupant questionnaire covered items relating to environmental and job satisfaction and various organizational productivity indices. The questionnaire items were generally rated on a 7-point Likert type scale, ranging from very unsatisfied to very satisfied. The data were collected between May 2010 and October 2011. Physical data were collected at a total of 977 workstations, and questionnaire responses were received from 2,545 occupants. A subsample of 230 physical measurement locations were matched to occupant responses. For more details regarding the data collection methodology, refer to Newsham et al. (2013).

The second, more recent, field study involved data collected from a large, conventional public-sector building located in the National Capital Region in Canada. Data were collected from occupants and representative workspaces in the building between October and November 2017. The data collection methodology in the second study was almost identical to that of the first field study. Physical measurements were conducted at a total of 265 workstations in the building. A total of 1,953 questionnaire responses were received from the occupants in this study. A subsample of 80 physical measurement locations were matched to occupant responses.

Previous researchers (e.g. Leder et al. 2016; MacNaughton et al. 2017; Holmgren, Kabanshi, and Sörqvist 2017) have consistently demonstrated differences in environmental satisfaction between conventional buildings and green buildings. As such, only data from conventional buildings in the first study was combined with the data from the second study to avoid potential confounding effects. This resulted in a total sample of 194 cases from 11 buildings in which physical data and occupant questionnaire data referred to the same workstation across the two studies. Sample sizes may differ between individual analyses as missing cases vary across questionnaire items. That is, the number of responses for any given questionnaire item may not total 194. Table 1 below shows the demographics of the participants in this sample.

Table 1. Demographic characteristics of the participants in the sample analysed in this paper

Age	*Sex*	*Education*	*Job Category*
18-29 (N=15) 20-39 (N=42) 40-49 (N=55) 50-59 (N=67) >60 (N=12)	Female (N=126) Male (N=65)	High School (N=23) Community College (N=31) University Courses (N=17) Undergraduate Degree (N=66) Graduate Degree (N=52)	Administrative (N=54) Technical (N=13) Professional (N=89) Managerial (N=34)

2.2 Data Analysis

North American standards and guidelines, to which these buildings would be expected to conform, were examined to evaluate their correlations with occupant environmental satisfaction. The ANSI/IESNA RP-1-12 American National Standard Practice for Office Lighting was used to examine satisfaction with lighting. The ANSI/ASA S12.2 American National Standard Criteria for Evaluating Room Noise standard was used to examine satisfaction with acoustics. The ANSI/ASHRAE 55 Thermal Environmental Conditions for Human Occupancy standard was used to examine thermal comfort. A summary of the recommended range of values for illuminance, sound, and thermal comfort in the standards is presented below in Table 2.

Table 2. List of standards/guidelines and recommended range

Standard/Guideline	*Recommended range*	*Aspect of IEQ*
ANSI/IESNA RP-1-12 (2012): American National Standard Practice for Office Lighting	300 to 500 lux (desktop illuminance)	Lighting
ANSI/ASA S12.2 (2008): American National Standard Criteria for Evaluating Room Noise	44 to 48 dBA (background noise)	Acoustics
ANSI/ASHRAE Standard 55 (2017): Thermal Environmental Conditions for Human Occupancy	$\leq$ 10% PPD $-0.5 \leq$ PMV $\leq +0.5$	Thermal

The lighting and acoustics reference values are self-explanatory in their interpretation. However, for the calculation of thermal comfort some assumptions were made. For clothing insulation (clo), a value of 0.5 (average) was assumed for data collected in the summer months, 0.7 (average) for data collected in the fall or spring, and 1.0 (average) for data collected in the winter. A metabolic equivalent (MET) value of 1.1 was assumed throughout. These are common assumptions for office conditions and sedentary office work in North America (ASHRAE 2017).

For the purposes of this study, specific items and parameters relating to environmental satisfaction were selected from the original questionnaires. This included three composite variables created by averaging the responses of multiple questions relevant to that aspect of the indoor environment: satisfaction with lighting, satisfaction with ventilation and temperature, and satisfaction with acoustics and privacy. For more detailed information on the contents of the subscale composite measures of indoor environment and their formulation, refer to Veitch et al. (2007).

The data were analyzed using multiple hierarchical regression. This procedure was selected because many predictor variables can be analyzed simultaneously. It allows for a predefined sequence of steps where the effects of individual predictors can be examined independently while their shared variance is considered. This approach has been used in similar published studies (Leder et al. 2016; Charles et al. 2006; Veitch et al. 2005). In general, hierarchical regression is an accepted practice as the researcher can select the predictors and their order of entry based on subject knowledge and the specific hypotheses of interest. All statistical analyses were performed using the IBM SPSS 24 Statistical software.

The predictor (independent) variables were input as three separate blocks to isolate the effects of each block on the outcome (dependent) variables. The first block of inputs consisted of demographic variables that have been shown in literature to have impacts on environmental satisfaction. The second block of inputs consisted of various workstation characteristics for similar reasons. The last block contained variables reflecting adherence to guideline values in the measured environmental variable of interest (e.g. whether desktop illuminance measurements were between 300-500 lux etc.).

3.0 RESULTS

3.1 Descriptive statistics

Table 3 summarizes the predictor variables used in this study. Window location is divided into workstations with and without windows. The windows in the sampled buildings were not operable. Workstation enclosure is separated into private workstations (full height walls and a door) and open workstations (all other configurations). Other workstation characteristics such as workstation size and wall partition were originally included as predictor variables in the analysis but were subsequently removed because of excessive multicollinearity (i.e. intercorrelation between predictor variables). In this sample, very few cases had sound levels greater than 44 dBA, and a separate category for such values was not large enough for statistical validity. As such, the acoustics limits were set to whether measured background noise levels were below recommendations. Table 4 provides the descriptive statistics of the recorded physical IEQ measurements used as inputs to the reference value variables in Table 3. Dependent (outcome) variables used in this study are summarized in Table 5. As previously stated, composite variables made up of averaged values across multiple questionnaire items were used.

Table 3. Summary of predictor variables

Variable	*Description*
Age	18-29 (N=15) 20-39 (N=42) 40-49 (N=55) 50-59 (N=67) >60 (N=12)
Sex	0 = Female (N=126) 1 = Male (N=65)
Window Location	0 = No window in workstation (N=108) 1 = Window in workstation (N=84)
Workstation Enclosure	0 = Open workstation (N=138) 1 = Private workstation (N=56)
Illum_Ref	0 = Outside of 300-500 lux (N=109) 1 = Within 300-500 lux (N=85)
SoundRef_Below	0 = Less than 44 dBA (N=135) 1 = Greater than or equal to 44 dBA (N=59)
Therm_Ref	0 = Outside of thermal comfort zone (N=111) 1 = Within thermal comfort zone (N=83)

3.2 Hierarchical Regression

The multiple linear regression results can be interpreted as follows. The columns under each *β* heading show the standardized regression coefficient (or slope coefficient) for a predictor variable. For every standard deviation increase in the predictor variable, *x*, there will be β^*x standard deviation increase in the outcome variable; larger regression coefficients represent larger correlations between the predictor variable and the outcome within that analysis. The asterisks present in the tables represent *p*-values (significance levels), with thresholds at 0.05, 0.01, and 0.001. *P*-values less than the significance level thresholds represent a statistically significant result. Tolerance represents the redundancy of a predictor variable in the overall analysis; the smaller the value, the more redundant its contribution to the regression (values <0.1 are typically used as a criterion for predictor exclusion). Effect sizes (R^2) are interpreted using the small (1%), medium (9%), and large (25%) effect size criteria from Cohen (1988).

Table 6 below shows the analysis results for satisfaction with lighting. The results show that occupants in offices with windows had greater lighting satisfaction. Data from this table also show that occupants had higher satisfaction with lighting in workstations where the measured desktop illuminance values were within the recommended range of 300-500 lux.

Table 4. Descriptive statistics of physical IEQ measurements

Variable	*Mean*	*Std. Dev.*	*Min.*	*Max.*	*N*
Desktop Illuminance (lux)	487	276	58	1631	194
Sound Level (dBA)	42.1	3.8	33.4	52.7	194
Air Velocity (m/s)	0.12	0.05	0.02	0.37	194
Radiant Temperature (°C)	22.9	1.2	19.1	27.6	194
Air Temperature (°C)	22.9	1.0	18.9	27.4	194
Relative Humidity (%)	28	8	15	54	194

Table 5. Descriptive statistics of outcome variables

Variable	*Mean*	*Std. Dev.*	*Min.*	*Max.*	*N*
Satisfaction with lighting (average of 5 questions)	4.9	1.1	1	7	191
Satisfaction with acoustics and privacy (average of 10 questions)	4.2	1.3	1	7	194
Satisfaction with ventilation and temperature (average of 3 questions)	3.9	1.5	1	7	194

Table 6. Satisfaction with lighting regression results

	β	*β*	*β*	*Tolerance*
Age	0.00	-0.04	-0.02	0.95
Sex	0.12	0.12	0.10	0.98
Window		0.29***	0.32***	0.93
Workstation Enclosure		-0.03	-0.04	0.96
Illum_Ref			0.16*	0.92
R^2 Change	0.01	0.08***	0.02*	
Total R^2	0.01	0.10***	0.12***	
Adjusted R^2	0.00	0.08***	0.10***	

Notes: Tolerance values are shown for variables at the final step. N = 190, *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001.

Table 7 below shows the analysis results for satisfaction with acoustics and privacy. In the first step of the analysis females were found to be less satisfied with acoustics & privacy than their male counterparts. However, this effect was not sustained through the rest of the hierarchical regression. A positive correlation was found between workstation enclosure and satisfaction with acoustics and privacy, occupants in private workstations reported higher levels of satisfaction than those in open workstations. No statistically significant differences in acoustic satisfaction were observed between workstations with measured background noise levels less than 44 dBA and workstations above 44 dBA.

Table 8 below shows the analysis results for satisfaction with ventilation and temperature. Sex was significantly correlated with satisfaction with ventilation & temperature. Male occupants were typically more satisfied with their thermal environment than females. The results also show a correlation between workstation enclosure and satisfaction. Occupants in private workstations were less satisfied with ventilation and temperature than their open workstation counterparts. No statistically significant differences in satisfaction were observed between measured thermal conditions within, and outside of, the thermal comfort zone suggested in the ASHRAE Standard 55.

Table 7. Satisfaction with acoustics and privacy regression results

	β	*β*	*β*	*Tolerance*
Age	-0.08	-0.13	-0.13	0.96
Sex	0.15*	0.13	0.13	0.98
Window		0.04	0.04	0.97
Workstation Enclosure		0.35***	0.35***	0.97
SoundRef_Below			0.05	0.99
R^2 Change	0.03	0.12***	0.00	
Total R^2	0.03	0.15***	0.15***	
Adjusted R^2	0.02	0.13***	0.13***	

Notes: Tolerance values are shown for variables at the final step. N = 191, *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001.

Table 8. Satisfaction with ventilation and temperature regression results

	β	*β*	*β*	*Tolerance*
Age	-0.04	-0.02	-0.03	0.95
Sex	0.19**	0.20**	0.22**	0.96
Window		-0.01	-0.01	0.97
Workstation Enclosure		-0.18*	-0.17*	0.97
Therm_Ref			-0.09	0.96
R^2 Change	0.04*	0.03*	0.01	
Total R^2	0.04*	0.07**	0.08*	
Adjusted R^2	0.03*	0.05**	0.05*	

Notes: Tolerance values are shown for variables at the final step. N = 191, *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001.

4.0 DISCUSSION

The results of the lighting regressions were largely in agreement with expectations. The positive effects of natural daylighting and windows on occupant satisfaction have been shown across many studies (Galasiu and Veitch 2006; Veitch et al. 2005; Yildirim et al. 2007). The results also showed that occupants were significantly less satisfied with lighting when the measured desktop illuminance levels were not within recommended thresholds as specified in IESNA RP-1-12 (2012). Newsham et al. (2008) reported similar findings in a study of conventional open plan offices. This result reinforces the validity of the limit thresholds outlined in the IESNA document.

The most obvious finding from the results of the acoustics regression was the correlation between more enclosed workstations and higher satisfaction with acoustics and privacy. This effect was consistently observed across every step of the hierarchical regression. These results corroborate the findings of prior work (Leder et al. 2016; Frontczak et al. 2012; Kim and de Dear 2013). Nevertheless, industry trends continue to move practice away from private to more open workstations. The desire to have more open workstations is driven by cost-savings on real-estate and the belief that more open workspaces support more communication amongst coworkers and foster innovation (Waber, Magnolfi, and Lindsay 2014). However, this belief is largely unsupported by recent objective research (e.g. Bernstein and Turban 2018; Kim and de Dear 2013). Contrary to expectations, this study did not find any significant differences in satisfaction between measured sound levels within, and outside of, ASA S12.2 (2008) recommended thresholds. One possible explanation is that the range of the measured sound levels within this study was limited, and only a small number of workstations had high levels of measured background noise (refer to Table 4). In a study using different noise level intervals, Newsham et al. (2008) also found background noise to not significantly influence acoustic satisfaction.

Consistent with literature, the regression analysis of thermal satisfaction found that male occupants were more satisfied. Other researchers have reported similar findings in their studies (Kim et al. 2013; Leder et al. 2016; Newsham et al. 2008). This observed result may be related due to several season such as biological differences between the sexes, or differences in clothing attire (i.e. insulation), particularly during the cooling season when the A/C is in operation. The effects of workstation enclosure observed in this study support the results of Kim and de Dear (2013), where occupants of private workstations were less satisfied with their thermal environment. This is also in agreement with the findings of Charles et al. (2006), where partition height in open-plan offices was negatively correlated with satisfaction with ventilation and temperature. A possible explanation is that full height walls could prevent good air mixing and thermal conditioning throughout the spaces from the mechanical systems. No differences in satisfaction were found between indoor environment measurements that were within and outside of ASHRAE Standard 55 (2017) comfort criteria. While unexpected, these results are consistent with Cheung et al. (2019), who found PMV-PPD to be a poor indicator of thermal sensation and satisfaction. The results of our study may be further explained by the fact that approximately half of the data samples used in this study were obtained from a single building, measured across a three-week period. This could reduce the range of measured thermal conditions, diminishing possible correlations in the data. Furthermore, unlike ASHRAE Standard 55 (2017) which focuses purely on thermal comfort, the composite measure of satisfaction with ventilation and temperature used in this analysis refers not only to the thermal environment, but also air quality. While ventilation systems in large North American office buildings typically regulate both air quality and the thermal environment, it is possible that the impressions of air quality separate from thermal issues may have diluted any observed effects. Assumptions of clothing and activity levels also may not have been entirely reflective of actual conditions, potentially resulting in inaccurate PMV and PPD calculations.

It is unexpected that no significant differences in satisfaction were observed by staying within the reference criteria for acoustics and thermal comfort, and it prompts a discussion on some of the possible reasons why this occurred. It is possible that the sample size wasn't large enough to establish consistent results in the data. Prior research using a larger dataset with similar data collection methodologies did find significance in various physical indoor environmental predictors (Newsham et al. 2008; Charles et al. 2006; Veitch et al. 2005). Observing the effect size of these prior studies, the lighting regression in this study had marginally more explained variance. This study had an adjusted R^2 of 0.095 compared to an adjusted R^2 of 0.092 found by Veitch et al. (2005). The thermal comfort regression in this study had less explained variance, an adjusted R^2 of 0.051, compared to an adjusted R^2 of 0.111 found in Charles et al. (2006). This can likely be attributed to the smaller number of predictor variables used in this study.

Moreover, physical measurements were performed over a 10-15 minute interval. This method is used consistently in research as a necessary trade-off in order to capture reasonable sample sizes. However, it does assume that the short sampling period is representative of the environment over longer periods. The conditions in some workstations may vary significantly both on a daily cycle (for example east or west facing) and over different seasons. It is likely that the survey responses in this sample were framed with respect to longer-term conditions. Therefore, if the 10-15 minute sample was not representative of longer-term conditions this would introduce a source of error into the data.

Furthermore, people adapt to make themselves more comfortable. There could potentially be such adaptations that were not measured as part of this methodology. In terms of office acoustics, occupants could wear headphones or change their position within a workstation to avoid loud spots. Similar considerations could apply to thermal comfort. While the assumptions of clothing values and metabolic rates are typical for indoor office work conditions, they might not be entirely representative of reality. Occupants can modify their thermal sensations by wearing additional or fewer layers of clothing to make themselves more comfortable. Lighting levels may also be easily adjustable by occupants with the use of individual task lights or shading devices, or occupants might find specific locations within a workstation to avoid glare.

Given the improved availability of relatively cheap sensors in recent years, perhaps adjustments to the data collection methodology could be made to provide more insights in future POE studies. For example, the use of more longitudinal sensors could alleviate some of the issues regarding the changing indoor environment conditions over time. Wearable sensors could provide more accurate data on local indoor environmental conditions, help provide more realistic metabolic rate estimates based on heart rate, and provide more detailed information on individual behaviour and characteristics.

CONCLUSIONS

This study originally set out to evaluate the relationship between various IEQ guideline thresholds on occupant satisfaction. The analyses suggest that adherence to the illuminance recommendations of 300-500 lux by the IESNA RP-1-12 (2012) standard correlated with higher levels of occupant satisfaction with lighting. In terms of sound level and thermal comfort, the results of this study did not show any significant increases in occupant satisfaction when the measured physical parameters were within recommended ranges (ASA S12.2, ASHRAE 55). Whilst this study did not confirm the field validity of acoustics and thermal comfort reference criteria, it did confirm the expected effects of sex, window proximity, and workstation enclosure. Females had lower levels of satisfaction with ventilation and temperature, offices with windows were correlated with increased lighting satisfaction, and more enclosed workstations were associated with increased satisfaction with acoustics and privacy, but decreased satisfaction with ventilation and temperature.

ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank the following individuals at NRC for their contributions: Chantal Arsenault, Anca Galasiu, Sandra Mancini, and Alexandra Thompson. We would also like to thank the managers and employees who took time out of their day to participate in the studies.

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