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PARK, J <http://orcid.org/0000-0003-3421-7294>, LOFTNESS, V, AZIZ, A and WANG, TH

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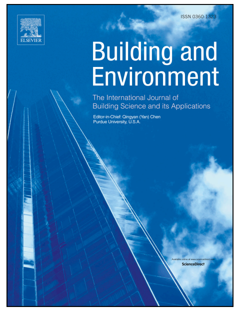

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Critical Factors and Thresholds for User Satisfaction on Air Quality in Office Environments

Jihyun Park[a]; Vivian Loftness[b]; Azizan Aziz[b]; Tsung-Hsien Wang[c*]

[a] Department of Natural and Built Environment, Sheffield Hallam University
Howard Street, Sheffield, S1 1WB, UK

[b] School of Architecture, Carnegie Mellon University
5000 Forbes Avenue, Pittsburgh, PA 15213, USA

[c] School of Architecture, University of Sheffield
Western Bank, Sheffield S10 2TN, UK

[*] **Corresponding Author**

Tsung-Hsien Wang, PhD

Email: tsung-hsien.wang@sheffield.ac.uk

Phone: +44 (0)7543 715664

Abstract

Indoor air quality of the workplace is highly linked with occupants' health, comfort and satisfaction. To maintain the good indoor air quality of buildings, Post Occupancy Evaluation (POE) is often combined with environmental measurements to holistically examine existing performance conditions in relation to occupants' satisfaction. The Centre for Building Performance and Diagnostics (CPBD) at Carnegie Mellon University conducted post occupancy evaluations for over 1600 workstations in 64 buildings using the National Environment Assessment Toolkit (NEAT)—a suite of three tools for workstation IEQ measurements, Technical Attributes of Building Systems (TABS) and occupant satisfaction surveys.

The rich dataset generated by NEAT was employed in this study to perform multivariate regression and multiple correlation coefficient analyses on Indoor Air Quality (IAQ). We examine the relationship between measured and perceived IAQ indices, as well as interdependencies between IAQ indices and occupant satisfaction variables of significance. Among measured IAQ indices, CO_2 and particulates are identified as critical factors for user satisfaction. In particular, the analyses revealed that the CO_2 threshold of 582 ppm is the highest occupant satisfaction in office buildings. To ensure good air quality in office buildings, our findings recommend "Operable window", "Dedicated exhaust", "Individual return air diffuser density" and "Low/medium partition height" as applicable design guidelines. Through this study, we demonstrate the effectiveness of integrating POE with environmental measurements to systematically develop a rich database leading to critical thresholds and design guidelines for highest occupant satisfaction.

Keywords

indoor environmental quality; indoor air; post occupancy evaluation; carbon dioxide; particulates; occupant comfort.

Highlights

- Provides practical IAQ assessment methods and procedures centered on the occupants' perspective.
- Reveals concurrent air quality features in the office environment, and defines correlations between occupant perception on air quality and measured data.
- Prioritizes critical features on IAQ evaluation in the field to enhance occupant satisfaction.
- Proposes metrics and guidelines for IAQ standards that capture new thresholds that impact building occupants' satisfaction on air quality.
- Provides design guidelines and maintenance and operation protocols for designers, building owners and facility managers to maintain higher IAQ satisfaction in the office environment.

1 Introduction

Indoor air quality (IAQ) in the workplace is critical for occupants' health and productivity [1-8]. In general, sensory perception reflects immediately perceived air quality. Within a minute of a change in air quality, there will be an instant response such as sneezing or yawning if it is uncomfortable [9]. However, occupants cannot easily detect some pollutants [10-12], among which a threshold is assumed: if the exposure is below the threshold level, no response is expected. Given that CO_2 is odourless and colourless, people cannot easily discern the concentration level, which can have a strong impact on occupants' health [12]. For instance, the higher the concentration level, the higher the rate of sick building syndrome (SBS) symptoms [13].

Complementing field measurements with post-occupancy evaluation (POE) can provide insights to better understand the correlations between perceived and measured IAQ conditions [15-20]. In particular, carbon monoxide (CO), carbon dioxide (CO_2), total volatile organic compounds (TVOC), and particulates (PM2.5, PM10) are critical objective IAQ indexes that are often considered in the field POE [9, 15, 21, 22]. In Table 1, we summarize studies that investigated critical indicators concerning IAQ evaluation for occupant satisfaction.

Table 1 Indicators of air quality assessment

Indicator	***Goal***	***IAQ related indicator***	***Sources***
CO_2 (ppm)	No concern of CO_2 concentration from high occupancy or materials	CO_2 level in populated rooms	[23], [22] [24], [25], [26], [27], [28]
		Quality of ventilation filters	[29] [30]
		Measuring air flow rates	[26], [31], [32], [33], [34], [35]
		Air exchange effectiveness	[4][25] [26]
		Individual controllability of ventilation	[24] [36] [37]
		Observation of smells (bioeffluents)	[22]; [24], [27, 38]
CO (ppm)	No CO of concern	CO symptomatic (not fatal) cases are mistaken for the flu.	[39]
		Symptoms can be delayed for 20 days after exposure	[40], [12], [41]
Particulates (ug/m3)	No PM 2.5, PM 10 of concern	Significant complaints in sore throat, eye irritation, and nervousness (PM10)	[42], [10]; [43, 44], [45]

Indicator	*Goal*	*IAQ related indicator*	*Sources*
		Strong correlation between PM 2.5 and perceived air quality	[42], [35], [45] [46]
		Cleaning of duct system, filter exchange, Carpet	[39], [47]
VOCs (ug/m3)	No TVOC of concern	Sore throat, eye irritation, and nervousness	[48], [49], [50], [51], [52], [53]
		More sensitive to atopic people (skin)	[54]
		Adequate carpet material and cleaning methods	[24], [32]

Table 2 summarizes air quality indices from standards and guidelines for air quality evaluation in office buildings. In general, good indicators can help identify problems, define priorities, and monitor progress over time in reaching goals [57-59]. For example, CO2 concentration, as one of the most critical indicators of building IAQ, relates to the effectiveness of the ventilation rate of the building, and is associated with sick building syndrome symptoms such as eye irritation, headache, throat irritation, mental fatigue, nausea and dizziness [22, 35, 60]. In a 2002 study, Apte et al., showed that for every 100 ppm decrease in the differential between indoor and outdoor carbon dioxide concentration (dCO2), office workers experienced fewer SBS symptoms, including 60% fewer reports of sore throat and 70% fewer reports of symptoms of wheezing ($p<0.05$) [61]. Satish et al. [62] identified that CO2 affects decision making at thresholds of 600 ppm, which is below the normally accepted comfort range of 1000 pm [63].

Table 2 Summary Table of Air Quality Standards for Office buildings

	Indices	**Assessment Guidelines**	**Sources**
Air Quality	Carbon Dioxide	700 ppm above outdoor CO_2 level	ASHRAE
		< 800 ppm (indoor CO2 level)	EPA
		< 1000 ppm (indoor CO2 level)	EPA, CEN, SRER
		< 700/900/1200 ppm	FiSIAQ
		< 5000 ppm	OSHA, NOISH
		350 ppm above outdoor CO_2 level	SRER
	Carbon Monoxide	< 5 ppm	SRER
		<8 ppm	FiSIAQ
		< 9 ppm	EPA, NHMRC
		1.7/ 8.7 ppm	HKSAR
	Total Volatile Organic Compounds	< 200 ug/m^3 above outdoor TVOC concentration	EPA

	< 200/600 (8 hours)	Hong Kong
	< 500 ug/m^3 (1hour)	NHMRC
PM 2.5	≤ 10 ug/m^3	SRER
	≤ 15 ug/m^3	ASHRAE
	≤ 1,665,278 #/CF or 20 ug/m^3	Aircuity
PM 10	< 50 ug/m^3	EPA
	< 20/40/50 ug/m^3	FiSIAQ
	≤ 17,204 #/CF or 40 ug/m^3	Aircuity
Total Particulates	< 20 ug/m^3	EPA

In this study, through conducting field measurements to capture existing IAQ indices regarding user satisfaction, we aim to investigate refined thresholds of IAQ indices leading to highest user satisfaction. By further cross-examination with Technical Attributes of Building Systems (TABS), our ultimate goal is to identify applicable design guidelines leading to future healthier built environments.

2 Data Collection and Analysis Methods

2.1 IEQ field data collection

The Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon University (CMU) has collected objective and subjective data on the IEQ at individual workstations in public and private sector buildings. Three different kinds of data were collected to construct an SQL database, consisting of occupant satisfaction surveys, technical attributes of building systems, and workstation's IEQ measurements [6]. For each workstation, we collected thermal, air, visual, acoustic, and spatial quality survey data with a unique identifier. In total, 29 user surveys, 110 building condition surveys, and 15 measured IEQ variables were collected. They were combined in a database to explore the correlations between occupants, the technical attributes of the building systems, and the measured indoor environmental quality [64]. This rich database was created based on POE field measurements, dating from 2003 to 2014 [65]. Detailed information regarding three datasets was published in Park et al. [66]. In this paper, findings on the indoor air quality are further analyzed. Table 3 illustrates three data sets considered for indoor air quality analysis from 1,601 workstations in 64 buildings. Buildings were selected with the following three criteria: (1) Work Setting: White-collar office; (2) Type of organization: federal offices (*n* = 33), private sector financial, sales, and marketing; (3) Size of office: small- and medium-sized office (less than 500 m).

Table 3 Data sets considered for each workstation

	COPE User satisfaction survey	TABS Technical Attributes of Building Systems	NEAT IEQ measurements
Air Quality	Q. Overall Air quality in your work area Q. Air movement in your work area Q. Cleanliness Q. Odor Very Dissatisfied- Dissatisfied- Somewhat Dissatisfied- Neutral- Somewhat Satisfied - Satisfied - Very Satisfied (7-scale user satisfaction)	• Filter efficiency • Air systems • Dedicated exhausts • Pollution source management • Outdoor air management • Operable windows • Room air diffusion methods • Supply air diffuser density • Return air diffuser density • Outdoor air management • Level of maintenance HVAC • Diffuser Density • Diffuser Alignment • Window Quality	• CO_2 (ppm) • CO (ppm) • TVOC (μg/m^3) • Radon (pCi/L) • Ozone (ppm) • Particulates (μg/m^3)
General Information	Q22. Age 20~29, 30~39, 40~49, 50~59, 60~69, 70 + Q23. Gender Female-Male Q24. Job category Administrative- Technical- Professional-Managerial Q25. Highest education level High School- Community College- Some University- Bachelor Degree- Graduate Degree- Doctorate Q26. My department is a good place to work Q27. I am satisfied with my job Strongly Disagree- Disagree- Somewhat Disagree - Neutral- Somewhat Agree - Agree - Strongly Agree	• Year built • Construction type • Floor-to-floor height Floor-to-ceiling height • Year of last building renovation • Building shape and depth	

The portable suite of instruments on the NEAT—National Environmental Assessment Toolkit—cart was deployed at the sampled workstation to collect IEQ measurements, as shown in Figure 1. A data logger connected to a tablet computer recorded data from the instruments for analysis [67]. The specifications of the measurement instrumentation used in this study are listed in Table 4.

While the physical measurements were recorded, occupants were asked to sit nearby and to complete the Cost-effective Open-Plan Environments (COPE) questionnaire, developed by National Research Council Canada (NRCC) [68].

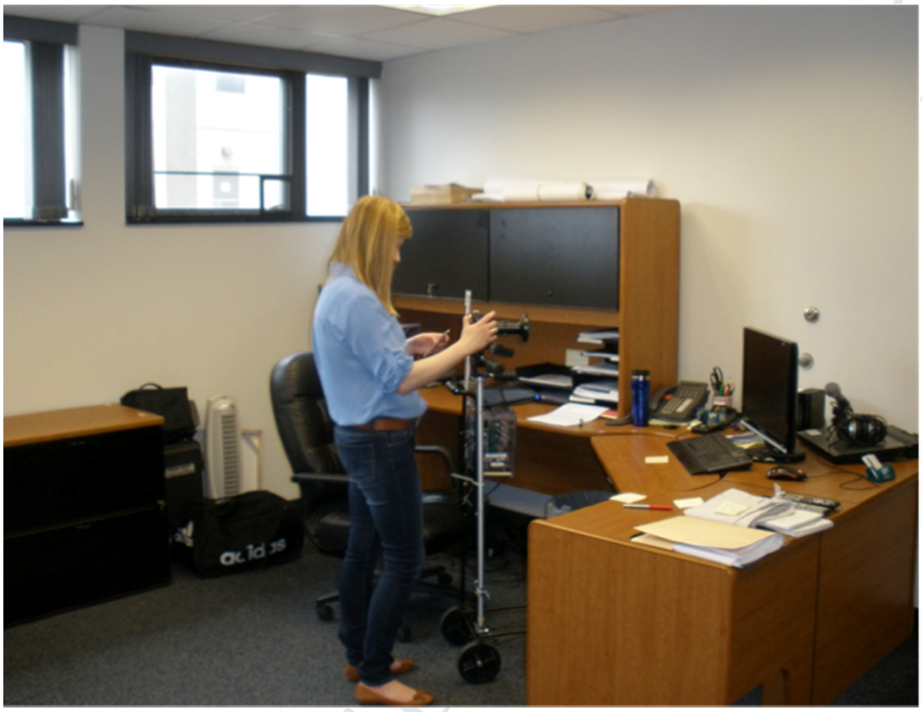


Figure 1 Image of IEQ measurements in the field with CMU's National Environmental Assessment Toolkit

Table 4 Specifications of the air quality measurement instrumentation

Air Quality	Measurement Range	Brand Name	Accuracy
CO_2	0 to 10,000 ppm	Telaire	± 3 %
CO	0 to 600 ppm	Transducer Technology	1 ppm
PM2.5	0 to 1,000 μg/m^3	Shinyei	± 25 %
PM10	0 to 1,000 μg/m^3	Shinyei	± 25 %
TVOC	0 to 2,000 μg/m^3	ETR GmbH	±10%
Air speed	0 to 200 m/s	Testo	± 5%

For the building systems survey, the CBPD team developed expert walkthrough worksheets—Technical Attributes of Building Systems (TABS)—to ensure that comparable data was recorded for the attributes of building systems that affect air. Appendix A shows TABS questionnaires for air quality evaluation of the building, and

Appendix B presents ventilation and stressors in the workstations utilized in the field study.

2.2 Data Analysis

2.2.1 Variable Selection

Prior to analyzing three different types of field data, including user surveys (COPE), IEQ measurements from sensors (NEAT), and building condition data (TABS), data screening was performed. Correlation matrix analysis was used to identify featured patterns in a large amount of data. Figure 2 presents the data screening procedure using 104 K correlation analysis, and Table 5 shows the final screened variables selected in this study for air quality analysis.

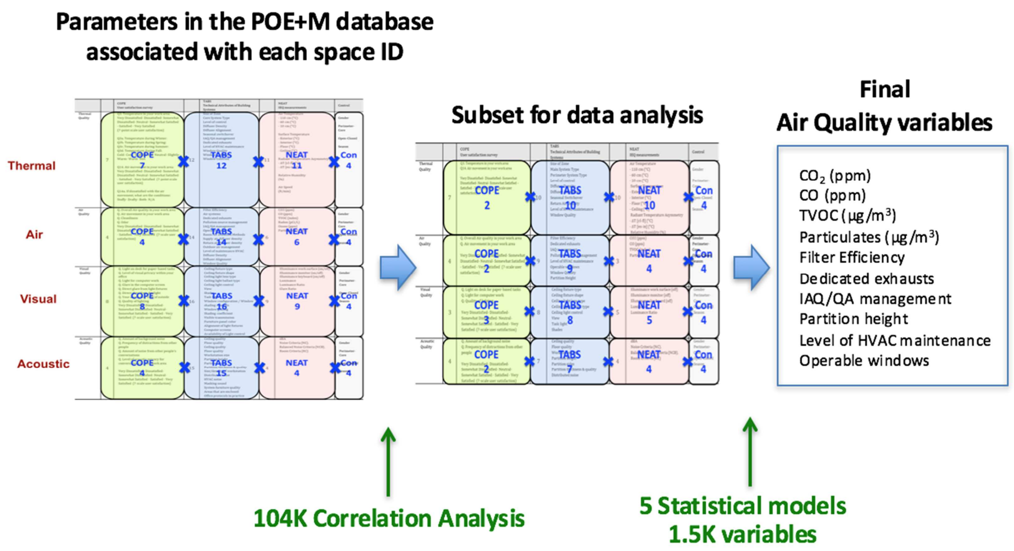


Figure 2 Data screening procedure

Table 5 Selected variables for air quality data analysis

	COPE User satisfaction survey	TABS Technical Attributes of Building Systems	NEAT IEQ measurements

	COPE User satisfaction survey	TABS Technical Attributes of Building Systems	NEAT IEQ measurements
Air Quality	Q. Overall Air quality in your work area Q. Air movement in your work area Very Dissatisfied- Dissatisfied- Somewhat Dissatisfied- Neutral- Somewhat Satisfied - Satisfied - Very Satisfied (7-scale user satisfaction)	• Filter Efficiency • Dedicated exhausts • Return air diffuser density • Partition height • Outdoor Air Management • Operable windows	• CO_2 (ppm) • TVOC ($\mu g/m^3$) • Particulates ($\mu g/m^3$)

Two COPE user satisfaction variables were selected: Overall air quality in the work area and Air movement in the work area. Six TABS variables included were filter efficiency, dedicated exhausts, return air diffuser density, partition height, outdoor air management, and operable windows. Three workstation's IEQ measurements were selected, including carbon dioxide, total volatile organic compounds and particulates.

To define the critical factors for occupants' air quality satisfaction, we developed four analysis models, as summarized in Table 6 [66]. We applied ordinary Least Squares and Ordered Logistic Fit in each model. Once critical factors were selected, we employed two-sample *t*-tests for binary variables and one-way ANOVA for multi-valued. The Chi-Square test and contingency analysis were then conducted to determine a significant difference between variables in user satisfaction.

Table 6 Four analysis models with objectives, diagrams and methods [66]

Model	Objective	Model Diagram	Statistical Method
MODEL 1	Correlation between user satisfaction and workstation IEQ measurements	NEAT → COPE	Ordinary Least Squares Ordered Logistic Fit One-way ANOVA, T-Test
MODEL 2	Correlation between user satisfaction and technical attributes of building systems	TABS → COPE	Ordinary Least Squares Ordered Logistic Fit Contingency Analysis Pearson Correlation
MODEL 3	Correlation between workstation's IEQ measurements and technical attributes of building systems	TABS → NEAT	Ordinary Least Squares Ordered Logistic Fit One-way ANOVA
MODEL	Correlation of user	TABS + NEAT → COPE	Ordinary Least Squares

Model	Objective	Model Diagram	Statistical Method
4	satisfaction with the combination of building attributes and workstation IEQ measurements		Ordered Logistic Fit

2.2.2 Model 1: Correlation between user satisfaction and workstation IEQ measurements on overall air quality

In model 1, two user satisfaction responses in the COPE questionnaires (overall air quality and air movement in the work area) and three IEQ measurements collected by NEAT instrumentation were first analyzed using ordinary least squares and ordered logistic fit. We then tested variables including gender, perimeter versus core workstation location, open-plan versus closed office type and season tested for correlation with workstation IEQ measurements. The result shows that occupants' satisfaction on air quality is highly related to measured indoor CO_2 level and concentration of particulates (Table 7).

Table 7 Data Analysis of Model 1: Overall air quality in the work area (n=902)

Criteria	Variables	Correlation coefficient	P-value	
NEAT measurements	CO^2	-0.0004	0.043	*
	TVOC	-0.0013	0.057	
	Particulates	-0.000288	0.047	*

* p≤0.05, **p≤0.01, ***p≤0.001

2.2.3 Model 2: Correlation between technical attributes of building systems and user satisfaction with overall air quality

In Model 2, the correlations between technical attributes of building systems and user satisfaction were tested using the eight physical building attributes assessed by the TABS record and user satisfaction responses investigated in the COPE questionnaires.

Table 8 shows the correlation between technical attributes of building systems and user satisfaction. Satisfaction with overall air quality is significantly correlated with five physical attributes: 1) Operable windows, 2) Window quality, 3) Dedicated exhausts, 4) Partition height and 5) Return air diffuser density.

Table 8 Relation between technical attributes of building systems and user satisfaction with overall air quality in the work area (n=814)

Criteria	Variables	Correlation coefficient	P-value	
Operable window	Operable vs None	-0.65	0.010	*
Window quality	Leaky vs. Moderate	1.27	0.041	*
	Leaky vs. Tight	1.23	0.043	*
Dedicated exhaust	None vs. some kitchen & copy	-0.27	0.232	
	None vs. all kitchen & copy	1.64	0.001	***
Partition height	Low vs. High	-0.57	0.006	**
Return air diffuser density	1 per 25+ vs.1 per 25	0.65	0.173	
	1 per 25+ vs.1 per 10	0.57	0.190	
	1 per 25+ vs.1 per 5	0.92	0.027	*
	1 per 25+ vs.1 per person	2.76	0.001	***
Filter efficiency	No filter vs. < 80 %	1.28	0.071	
	No filter vs. > 80 %, HEPA filter	1.14	0.107	
Outdoor air management	No outdoor air vs. < 10 cfm/person	0.09	0.299	
	No outdoor air vs. < 20 cfm/person	1.13	0.879	
	No outdoor air vs. < 30 cfm/person	1.05	0.224	
Natural ventilation	Yes vs. No	0.07	0.27	

Notes: * *p≤0.05*, ** *p≤0.01*, *** *p≤0.001*

2.2.4 Model 3: Correlation between and technical attributes of building systems and workstation air quality measurements

In this model, the correlations between the three IEQ measurements assessed by the NEAT instrument and eight physical building attributes investigated in the TABS record were analyzed using ordinary least squares and ordered logistic fit. The measurements of CO_2 data have significant relation on the operable window, dedicated exhausts, return air diffuser density, and filter efficiency, as shown in Table 9. The relation between TVOC and TABS showed similar trends (Table 10).

Table 9 Relation between TABS and NEAT, CO_2 (n=728)

Criteria	Variables	Correlation coefficient	P-value	
Operable window	Operable vs None	32.98	0.050	*
Dedicated exhaust	None vs. some kitchen & copy	-88.92	0.001	**
	None vs. all kitchen & copy	-126.43	0.001	**
Partition height	Partition height: Low vs. High	-0.97	0.948	
Return air diffuser density	1 per 25+ vs.1 per 5	-141.60	0.001	**
	1 per 25+ vs.1 per person	-232.95	0.001	***
Filter efficiency	No filter vs. < 80 %	-165.83	0.01	*
	No filter vs. > 80 %, HEPA filter	-296.05	0.01	*
Outdoor air management	No outdoor air vs. < 10 cfm/person	-29.83	0.104	
	No outdoor air vs. < 20 cfm/person	20.26	0.305	
	No outdoor air vs. < 30 cfm/person	33.17	0.145	
Natural ventilation	Yes vs. No	1.75	0.923	

Notes: * *p≤0.05*, ** *p≤0.01*, *** *p≤0.001*

Table 10 Relation between TABS and NEAT, TVOC (n=747)

Criteria	Variables	Correlation coefficient	P-value	
Operable window	Operable vs None	11.14	0.008	*
Dedicated exhaust	None vs. some kitchen & copy	-113.60	<0.001	**
	None vs. all kitchen & copy	-159.24	<0.001	**
Partition height	Partition height: Low vs. High	2.93	0.087	
Return air diffuser density	1 per 25+ vs.1 per 10	-79.24	0.0317	*
	1 per 25+ vs.1 per 5	-138.00	<0.001	***
	1 per 25+ vs.1 per person	-178.66	<0.001	***
Filter efficiency	No filter vs. < 80 %	-50.29	<0.001	*
	No filter vs. > 80 %, HEPA filter	-83.66	<0.001	*
Outdoor air management	No outdoor air vs. < 10 cfm/person	1.57	0.21	
	No outdoor air vs. < 20 cfm/person	-18.52	0.068	
	No outdoor air vs. < 30 cfm/person	-22.52	0.05	
Natural ventilation	Yes vs. No	1.65	0.1985	

Notes: * *p ≤0.05*, ** *p ≤0.01*, *** *p ≤0.001*

2.2.5 Model 4: Correlation of user satisfaction with combining technical attributes of building systems and workstation air quality measurements

The combination of TABS and IEQ measurements with user satisfaction on air quality was examined. The results showed that operable windows, window quality, dedicated exhaust, partition height, return air diffuser density, and CO_2 levels are significantly important, as shown in Table 11.

Table 11 Correlation of user satisfaction with combining technical attributes of building systems and measured indoor air quality (n=748)

Criteria	Variables	Correlation coefficient	P-value	
Operable window	Operable vs None	-0.51	0.032	*
Dedicated exhaust	None vs. some kitchen & copy	-0.20	0.436	
	None vs. all kitchen & copy	1.86	0.001	**
Partition height	Low vs. High	1.15	0.046	*
Return air diffuser density	1 per 25+ vs.1 per 10	2.21	0.167	
	1 per 25+ vs.1 per 5	0.87	0.039	*
	1 per 25+ vs.1 per person	1.03	0.047	*
Filter efficiency	No filter vs. < 80 %	0.63	0.177	
	No filter vs. > 80 %, HEPA filter	0.41	0.612	
IAQ management	No outdoor air vs. < 10 cfm/person	-0.31	0.820	
	No outdoor air vs. < 20 cfm/person	0.02	0.987	
	No outdoor air vs. < 30 cfm/person	1.23	0.081	
Natural ventilation	Yes vs. No	0.27	0.455	
NEAT measurements	CO_2	-0.00078	0.041	*
	TVOC	-0.0027	0.089	
	Particulates	-0.0000805	0.068	

Notes: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

3 Results and Discussion

Given user satisfaction data from 1,048 occupants in 64 office buildings, 52% of occupants responded “satisfied”, and 26% of occupants reported “dissatisfied” with their air conditions. The average satisfaction level is 4.6, which falls between ‘neutral’ and ‘somewhat satisfied’ on a 7-point scale survey (very dissatisfied, dissatisfied, somewhat dissatisfied, neutral, somewhat satisfied, satisfied, and very satisfied). Of those who were not satisfied with their air conditions, when we asked further, about 75% of occupants complained about stuffiness. The detailed information is provided in Appendix C.

Based on data analysis results from the four analysis models, we present and discuss the critical five factors for user satisfaction on the air quality as follows.

3.1 CO_2 level

From 1282 workstations in 64 buildings, 90% of the measured CO2 concentrations were within the ASHRAE 66 recommendation; yet only 52% of occupants reported satisfaction with their air quality. We investigated further for occupants with lower CO2 concentration levels, and identified the highest occupant satisfaction of 63% at a threshold of 582 ppm, as shown in Figure 3. No further improvement was found below the 582-ppm threshold from the collected data.

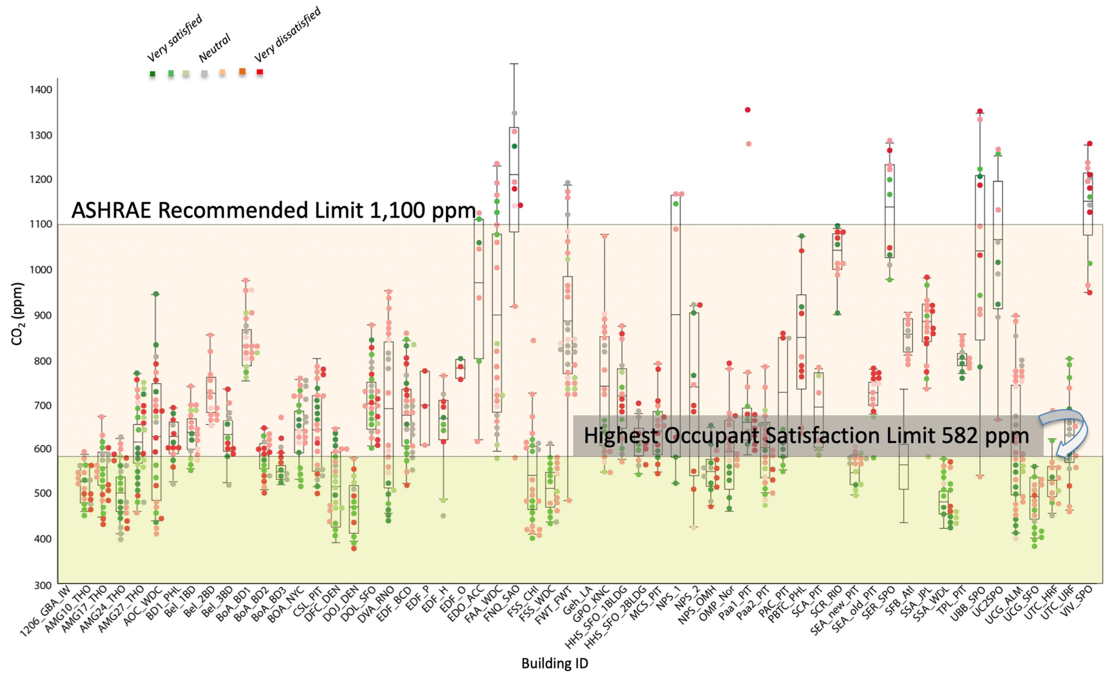
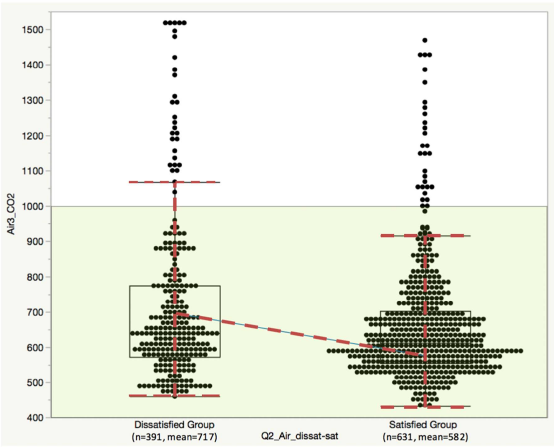


Figure 3 CO_2 measurements (n=1,282, mean= 670 ppm) with overall air quality satisfaction colored by 7-point scale.

In Figure 4, we illustrate the t-test analysis conducted on unsatisfied (Very Dissatisfied, Dissatisfied, and Somewhat Dissatisfied) and satisfied (Somewhat Satisfied, Satisfied, and Very Satisfied) groups. The analysis result shows that the difference is statistically significant with the p-value of 0.016 with 95% confidence intervals.



CO_2 level by User satisfaction

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Q2-2_Air	6	1125705	187618	5.171	<.0001*

Means for One-way Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Very Dissatisfied	94	807.3	26.9	751.5	857.2
Dissatisfied	132	835.4	20.2	690.8	870.0
Somewhat Dissatisfied	165	780.4	17.3	638.5	806.2
Neutral	260	677.2	12.9	574.9	725.6
Somewhat Satisfied	200	590.2	15.2	560.4	620.1
Satisfied	295	576.7	12	546.1	593.2
Very Satisfied	136	579.02	19.9	509.1	587.0

** significant shifts to satisfaction when CO_2 < **600** ppm*

Figure 4 Dissatisfied and satisfied group T-Test Analysis with overall air quality satisfaction linked to CO_2 concentration levels

Even though the measured particulate levels are not included in the final set of critical factors (p = 0.068, p>0.05), particulates are important factors among NEAT data (p=0.047), as shown in Table 7. As such, we further tested the critical limits for user satisfaction, and have summarized the results in Table 12.

Table 12 Dissatisfied and satisfied group T−Test analysis with overall air quality satisfaction linked to particulates (PM 10).

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Dissatisfied Group	165	47.711151	78.055675	6.0766261	35.712643	59.70966
Satisfied Group	270	28.038667	62.676221	3.8143533	20.528884	35.548449

Among 435 workstations, the average PM 10 level of the dissatisfied group was 47.71 $\mu g/m^3$, and the satisfied group was 28.03 $\mu g/m^3$. The difference is statistically significant with p=0.0041 and a confidence interval of 0.95. Overall, the mean value of all responses is 35.5 $\mu g/m^3$, which is within the EPA's recommendation range of 50 $\mu g/m^3$. Based on our findings, to keep the highest user satisfaction level, less than 28 $\mu g/m^3$ of measure PM10 should be used in the field.

3.2 Operable window

Access to an operable window can increase user satisfaction for air quality. The distribution for 590 questionnaire respondents in perimeter workstations showed that only 24% of occupants could open a window, and the other 76% of occupants could not. Out of all occupants, 66% would be more satisfied with operable windows ($n=590$. $p<0.01$). Figure 5 summarizes the contingency analysis (Table 13) with air quality and air movement by window operability. On average, occupants with an operable window have 17% higher user satisfaction on overall air quality and 25% higher satisfaction with air movement than those without.

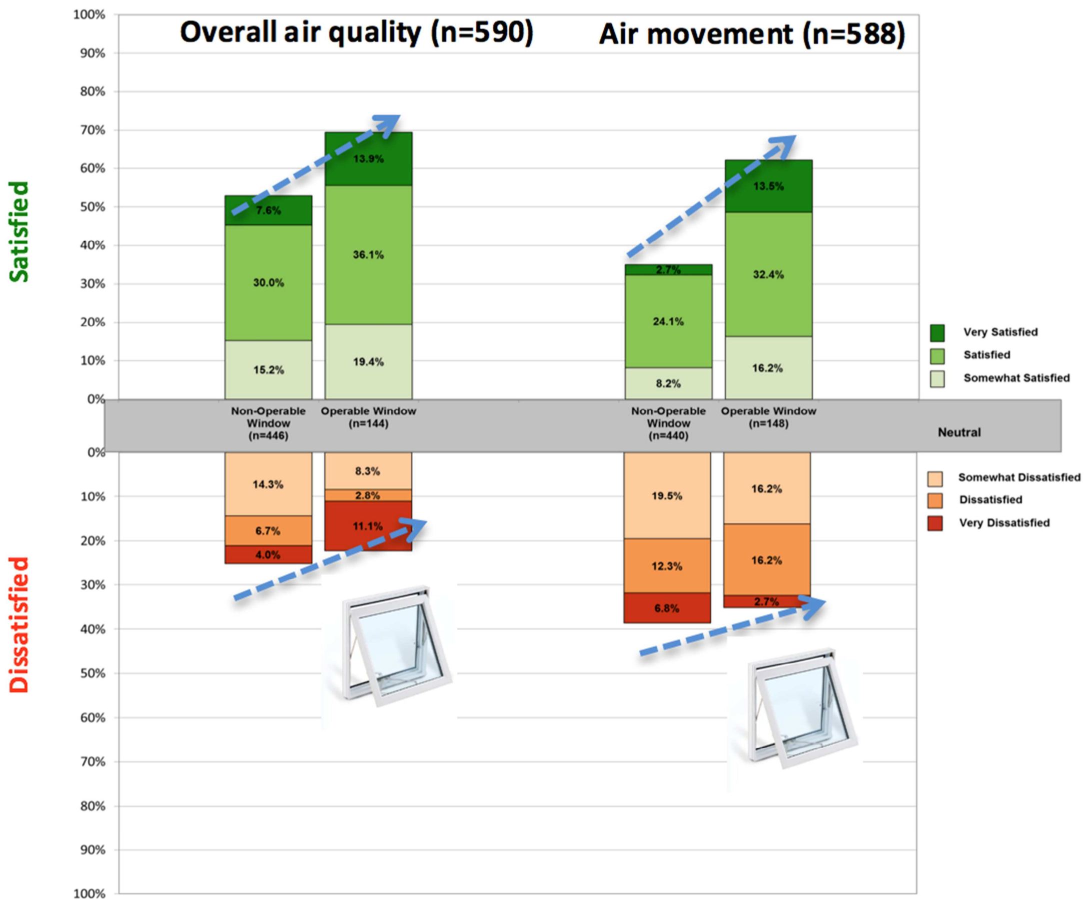


Figure 5 Satisfaction with overall air quality and air movement by operable window

Table 13 Contingency Analysis of User Satisfaction on Air quality by operable window

Satisfaction	n	Test Statistics	Chi-Square	Prob>ChiSq
Overall air quality	590	Likelihood Ratio	14.083	0.0287*
	590	Pearson	14.059	0.0290*
Air movement	588	Likelihood Ratio	22.143	0.0011**
	588	Pearson	20.823	0.0020**

Notes: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

3.3 Dedicated exhausts

Satisfaction for air quality increases with a space having dedicated exhausts for kitchens and copy areas. Among 665 respondents, 41% of workstations did not have dedicated spaces or exhausts for kitchen and copy areas, and these areas were near aisles or empty workstations. 46% of surveyed workstations had some dedicated areas for kitchen and copiers, but only 13% had all dedicated spaces with exhausts, as shown in Figure 6.

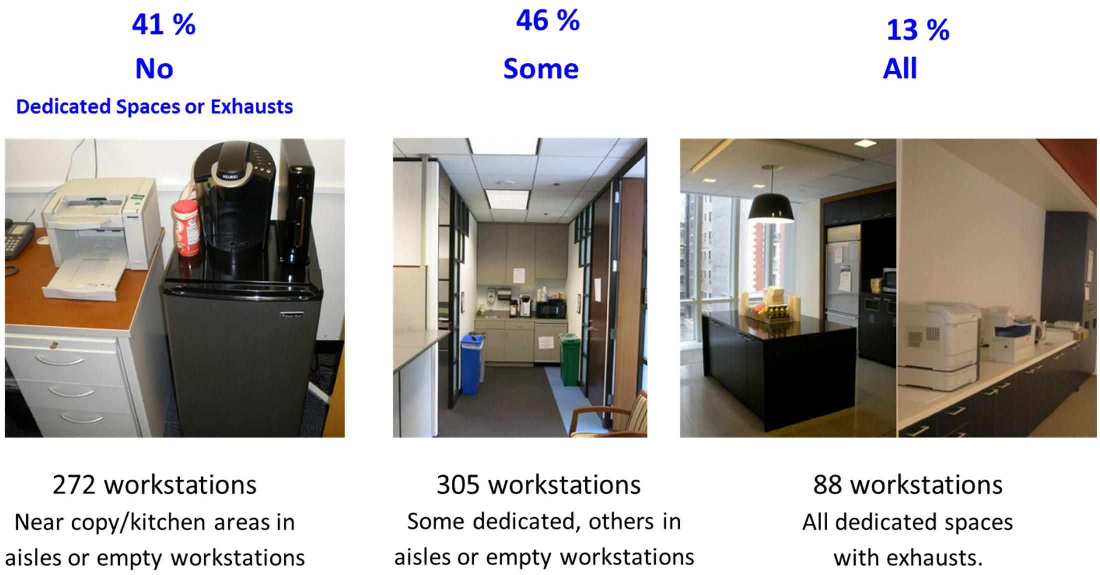


Figure 6 Distribution of dedicated exhausts in relation to 665 occupants in open-plan areas in 64 buildings

Occupant satisfaction with overall air quality is strongly linked to the design of dedicated copy and kitchen areas with exhaust, 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 exhaust had 30% higher satisfaction, while workstations which did not have dedicated spaces or exhaust, and copy and kitchen areas near aisles or empty workstations, showed lower satisfaction ($p<0.001$), as shown in Figure 7.

Figure 7 Relationship between air quality measurements and user satisfaction with overall air quality in your work area (n=902)

Table 14 Contingency Analysis of User Satisfaction on Air quality by Dedicated Exhausts.

Satisfaction	n	Test Statistics	Chi-Square	Prob>ChiSq
Overall air quality	665	Likelihood Ratio	57.287	<.0001***
	665	Pearson	52.266	<.0001*
Air movement	660	Likelihood Ratio	54.923	<.0001***
	660	Pearson	48.990	<.0001***

Notes: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

3.4 Return air diffuser density

Return air diffuser density represents the number of people covered by one diffuser unit for return air in TABS. In our finding, satisfaction for air quality increases as the number of people per return air diffuser unit decreases. The distribution of return air diffuser density from 1,036 questionnaire respondents in 64 buildings showed that 62% of the offices had a density of 5-10 people per unit. About 24% of workstations were controlled by one person for each unit, as shown in Figure 8. The left image of Figure 8 gives examples of sizes of net floor areas concerning the air diffuser density. For instance, one person per air diffuser unit could cover net floor areas of less than 15 m^2.

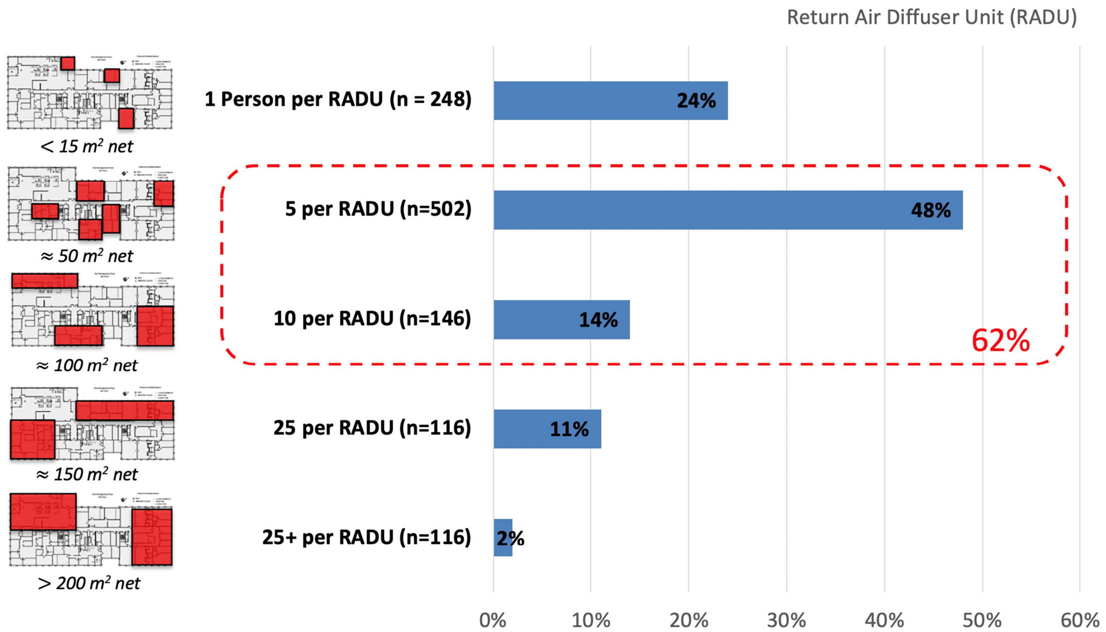
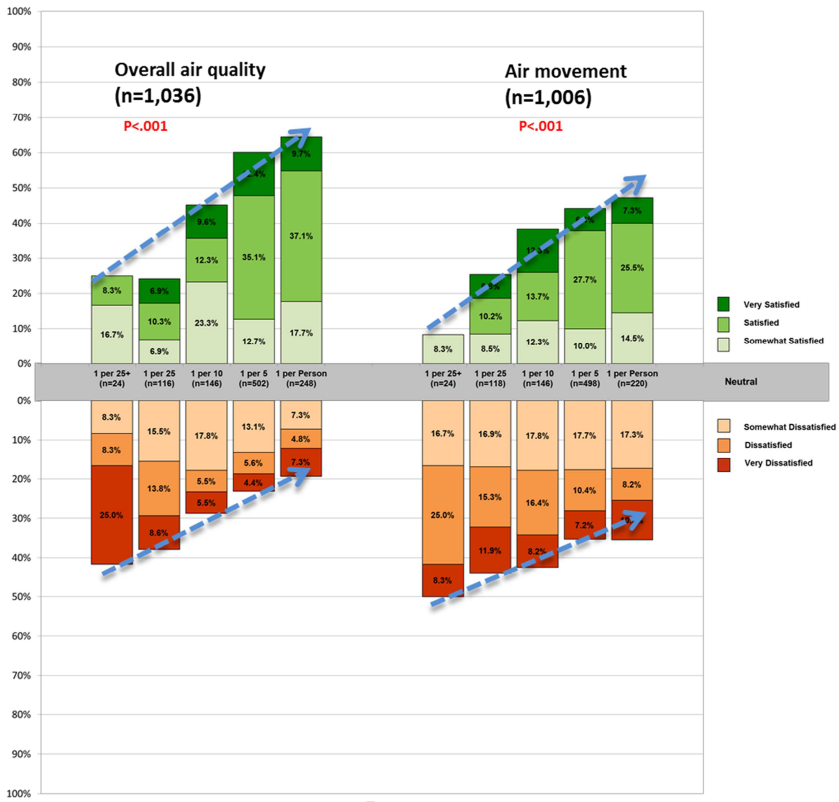


Figure 8 Distribution in "Return air diffuser density" for 1,036 questionnaire respondents in 64 buildings

Figure 9 shows that increasing the densities of return air diffusers is linked to satisfaction with overall air quality and air movement (n=1,036, p<0.001). The occupants who have an individual return air unit showed 65% satisfaction in overall air quality, while 25 people covered by one return air diffuser unit showed merely 25% user satisfaction. This result is also related to micro-zoning design strategies. When the size of the zone is smaller, more people are satisfied with their thermal quality [66]. We can expect that the smaller size of a zone can increase occupant satisfaction on thermal and air quality at the same time.



Contingency analysis of air quality by return air diffuser density

	n	Test Statistics	Chi-Square	Prob>ChiSq
Overall air quality	1,036	Likelihood Ratio	65.885	<0.0001***
-	-	Pearson	65.507	<0.0001***
Air movement	1,006	Likelihood Ratio	57.238	<0.001***
-	-	Pearson	59.008	<0.001***

Notes: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

Figure 9 User satisfaction on air quality by return air diffuser density for 1,036 Questionnaire respondents in 64 buildings

3.5 Partition height

The lower the partition height, the higher the satisfaction of overall air quality and air movement. In this study, the partition height was aggregated in two categories: low or medium height partitions and high partitions (behind which occupants cannot be seen) as shown in Figure 10. In total, 46% of workstations had low or medium height partitions and 54% had high partitions.

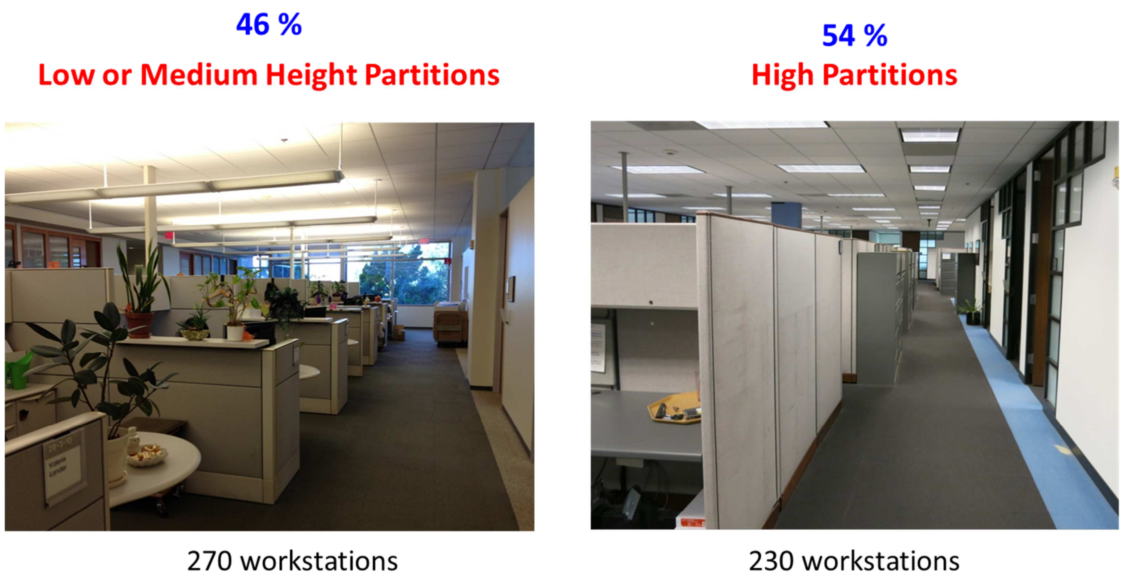
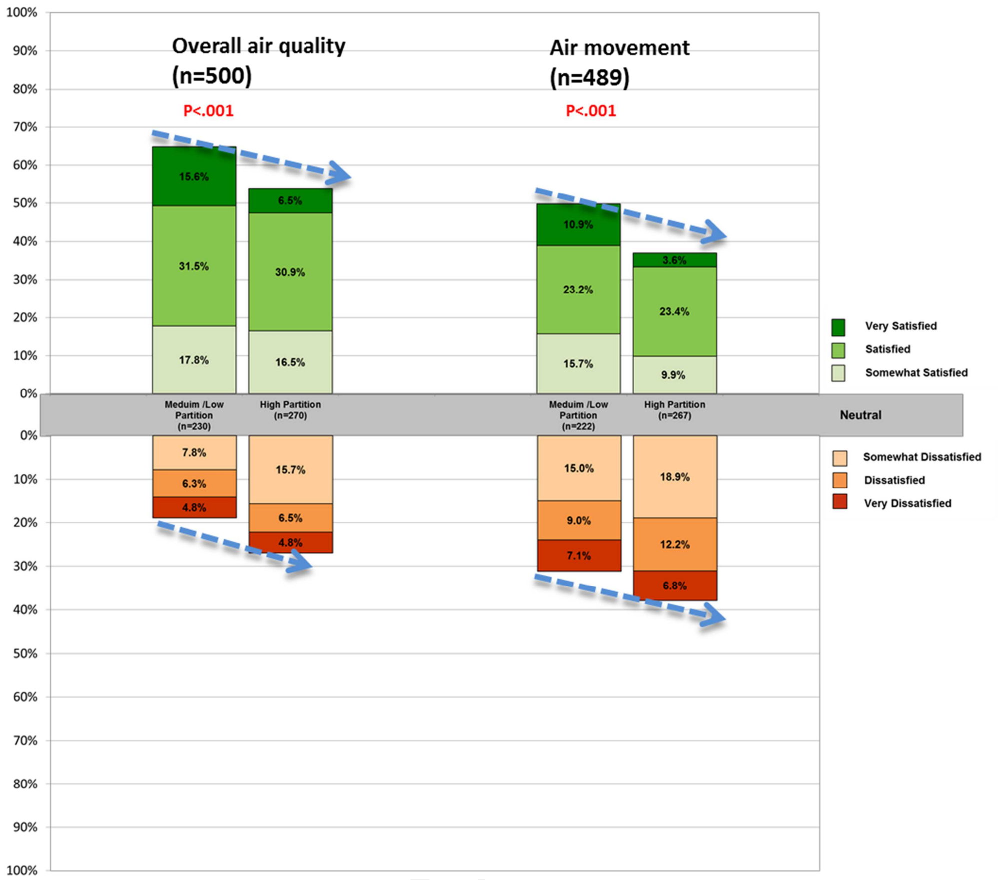


Figure 10 Distribution in partition height for 500 questionnaire respondents in open-plan workstations.

Given the NEAT database of 500 workstations in open-plan offices, the occupants who had low or medium partitions showed on average 15% higher user satisfaction for air quality ($n=500$, $p<0.01$), as shown in Figure 11. It is also related to the stuffiness of the workspace. Even though most of the measured values are with the ASHRAE 62-1 comfort level (less than 1000 ppm CO_2 level), people in high partitions showed less satisfaction in their air quality.



Contingency analysis of user satisfaction on air quality and air movement by partition height

	n	Test Statistics	Chi-Square	Prob>ChiSq
Overall air quality	500	Likelihood Ratio	16.823	0.0100**
-	-	Pearson	16.352	0.0120*
Air movement	489	Likelihood Ratio	16.677	0.0105*
-	-	Pearson	15.970	0.0139*

Notes: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

Figure 11 Satisfaction with overall air quality and air movement by partition height (p<0.01, n=500 in 64 buildings)

4 Conclusions and discussion

4.1 Conclusion

From user satisfaction surveys in 64 buildings, 52% of occupants overall responded "satisfied", and 26% of occupants reported "dissatisfied" with their air conditions. Five 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. From the existing database, the threshold of 582 ppm had the highest occupant satisfaction of 63%. User satisfaction could not be further improved below the threshold level.

- **Operable window**: Access to an operable window can increase user satisfaction with air quality. The distribution for 590 questionnaire respondents in perimeter workstations showed that only 24% of occupants could open a window, and 76% could not. Out of all occupants, 66% would be more satisfied with operable windows. On average, occupants with an operable window have 17% higher user satisfaction than those without an operable window.

- **Dedicated exhausts:** Satisfaction for air quality increases with dedicated exhausts for kitchens and copy areas. Among 665 respondents, 41% of workstations did not have dedicated spaces or exhausts for kitchen and copy areas, and these areas were near 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 was strongly linked to 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 exhaust had 70% user satisfaction, while workstations without dedicated spaces or exhaust and copy and kitchen areas near aisles or empty workstations scored 23% lower.

- **Return air diffuser density**: Reducing the number of people per return air diffuser unit increased user satisfaction for air quality. Overall, occupants who have an individual return air unit showed 40% higher user satisfaction than those with a density of 25 people per return air diffuser unit.

- **Partition height**: The lower the partition height, the higher 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 increased occupant satisfaction by 15% on a 7-point scale as compared to a high partition height.

As a result, we can conclude that occupant satisfaction can help inform design decisions. Among the technical attributes of building systems, the factors mentioned above are critical for user satisfaction and can support workspace design. For air quality, having an operable window, dedicated exhaust space for kitchen and copiers, high density of return air unit (less than five people per unit), and low partition height (less than 120 cm) are recommended.

In addition, we demonstrated that using occupant satisfaction surveys could redefine user comfort thresholds. From our dataset of 1,601 workstation's IEQ measurements and user satisfaction survey responses from 64 buildings, CO_2 level of 582 ppm, PM10 for 28 $\mu g/m^3$ for IEQ comfort thresholds are recommended for highest building occupant satisfaction. The thresholds for CO2 level is close to those shown in other studies, such as Satish and Fisk et al., with 600 ppm for decision making in office environments [62]. For PM10, our results support the recommendation level by the Finnish Society of Indoor Air Quality and Climate of S1 (20 $\mu g/m^3$) and S2 (40 $\mu g/m^3$) [23].

4.2 Research limitations and future work

There are some limitations in this study. First, the conclusions were based on field measurement data as opposed to controlled experiments and derived from an existing mixed-quality building stock. Second, data were collected from NEAT short-term spot measurements, not continuous monitoring. Third, data collection for technical attributes of building systems (TABS) was dependent on interpretations of experts in the field. For example, sometimes return air diffuser density was recorded by the perception of on-site building performance measurement professionals and not always from the building system drawings.

Based on current findings, we propose the following directions for future work.

- Development of a simplified post-occupancy evaluation field toolkit. Combining simple measurement instruments with user surveys can provide statistically significant insight into IEQ conditions at a fraction of the cost of complex field instrumentation. It can serve as a supplementary valuation to existing IEQ field measurements.

- Revise TABS and COPE to effectively align with field measurements for a better understanding of user satisfaction and comfort.

- Organizational (federal versus corporate), cultural (international), and building age variations will be further explored in our future work. For example, even though measured TVOC levels were high, occupants in some newly renovated buildings could still show relatively high IAQ satisfaction due to the improvement of the overall physical environment.

- Further Sick Building Syndrome symptoms data, collected from a long-term user satisfaction survey, are proposed for further in-depth analysis to investigate a holistic evaluation of IEQ conditions in the occupied space

Abbreviations

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

ANOVA: Analysis of variance

CBPD: The Center for Building Performance and Diagnostics

CCOHS: Canadian Center for Occupational Health and Safety

CEN: European Committee for Standardization

CIE: International Commission on Illumination

CMU: Carnegie Mellon University

COPE: Cost-effective Open Plan Environments

EPA: US Environmental Protection Agency

FiSIAQ: Finnish Society of Indoor Air Quality and Climate

HKSAR: The Government of the Hong Kong Special Administrative Region

IAQ: Indoor Air Quality

IEQ: Indoor Environmental Quality

NAAQS: National Ambient Air Quality Standards

NEAT: National Environmental Assessment Toolkit

NHMRC: National Health and Medical Research Council, Australia

NIOSH: National Institute for Occupational Safety and Health, US.

NRCC: National Research Council Canada

OSHA: Occupational Safety and Health Administration

OSL: Ordinary Least Squares

POE: Post occupancy evaluation

RADU: Return Air Diffuser Unit

SBS: Sick Building Syndrome

SRER: Sustainable Real Estate Roundtable

TABS: Technical Attributes of Building Systems

TVOC: Total Volatile Organic Compounds

WHO: World Health Organization

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Appendices

A. Selected Technical Attributes of Building Systems

General Base Data: for XXX floor, answer as many characteristics as possible for the most typical workstation

Year Built __________
Year of last building renovation __________
Gross Floor Area __________sf
Number of Floors above Grade __________
Number of Floors below Grade __________
Number of occupants including contractors __________
Hours Building is occupied on weekday __________am ~ __________pm
Is building conditioned when occupied on weekend
- ❑ Yes
- ❑ No

Site characterization:
- ❑ Urban
- ❑ Suburban
- ❑ Rural

Building was originally designed as:
- ❑ Office
- ❑ Retail
- ❑ Warehouse
- ❑ Residential
- ❑ Other:__________

Building shape and depth:
- __________ft long
- __________ft deep
- ❑ Court yard
- ❑ Atrium

Floor-to-floor height: __________ in.
Floor-to-ceiling height: __________ in.

Construction type:
- ❑ Curtain wall
- ❑ Masonry/ Concrete
- ❑ Wood
- ❑ Metal building system
- ❑ Modular/Prefabricated
- ❑ Other __________

Room Air Diffusion Methods:
- ❑ Mixing system
- ❑ Displacement Ventilation
- ❑ Under Floor Air Distribution and Task/Ambient Conditioning

Supply air diffuser density:
- ❑ >5 occupants per diffuser
- ❑ 3-5 occupants per diffuser
- ❑ 2 occupants per diffuser
- ❑ 1 occupant per diffuser
- ❑ ≥2 diffusers per occupant or relocatable

Return air diffuser density:
- ❑ <1 per 50 workstations
- ❑ 1 per 25-50 workstations
- ❑ 1 per 10-25 workstations
- ❑ 1 per 5-10 workstations
- ❑ > 1 per 5 workstations

Operable windows
- ❑ Yes, in use
- ❑ Yes, locked
- ❑ None

Mechanical systems:

Total chiller capacity: __________ tons (refrigeration)
Total boiler capacity: __________ Btu/hr
Number of Air Handling Unit: __________

Floor by floor AHU:
- ❑ Yes
- ❑ No

Seasonal switchover:
- ❑ Specific days for fall and spring
- ❑ As needed, <4 per year
- ❑ Whole building, as often as needed
- ❑ Each zone, as often as needed
- ❑ Each zone, continuous control
- ❑ Each occupant, continuous control

Economizer:
- ❑ Yes
- ❑ No

Outdoor Air Management:
- ❑ Operable window or infiltration only
- ❑ 10 cfm/person forced air
- ❑ 15 cfm/person forced air
- ❑ 20 cfm/person forced air
- ❑ Demand-based ventilation system (CO_2)

Air Filter Location:
- ❑ Returned air
- ❑ Outdoor air supply
- ❑ Mixed air upstream of coils
- ❑ Mixed air downstream of coil
- ❑ Supply air downstream fan

Filter Efficiency:
- ❑ No filter
- ❑ <80%
- ❑ 80% ~ 90%
- ❑ 90% ~ 95%
- ❑ >95% (HEPA filter)

Humidification
- ❑ Spray humidification
- ❑ Steam humidification
- ❑ Electrostatic humidification
- ❑ No humidification

Dehumidification
- ❑ Yes
- ❑ No

Level of maintenance HVAC system: (check that all apply)
- ❑ Rare maintenance
- ❑ Maintenance as needed
- ❑ Scheduled maintenance
- ❑ Maintenance with EMCS monitoring
- ❑ Preventive maintenance
- ❑ Retro-commissioning
- ❑ Continuous commissioning
- ❑ Other __________

Year HVAC was last updated: __________
And actions that were taken: __________

Pollution source management: (check all that apply)
- ❑ No pesticides used
- ❑ Low VOC fabrics/carpets
- ❑ Benign adhesives and paints
- ❑ Remote out gassing of new products
- ❑ No occupancy 130dedicated ventilation during renovation
- ❑ Green cleaning products/MSDS

B. Selected Workstation Data Sheet: Ventilation and Stressors

WORKSTATION DATA SHEET

SPACE ID:

Ventilation Stressors:

Ventilation

	Carbon Monoxide	ppm	
	Air Temerature 1.1m	°F	
	Carbon Dioxide	ppm	
	Particulates	index	
	Air Temperature 0.6m	°F	
	Relative Humidity	%	
	Air Temperature 0.1m	°F	
	TVOC	level	

Surface Temperature	Partition/Int. Wall	°F	
	Ceiling	°F	
	Floor	°F	
	Window/Ext. Wall	°F	

PPD	%	

WORKSTATION DATA SHEET

Space ID: **Date:**

Partial Shot

Full Shot

General Comments

Gender of Occupant: ☐ Female ☐ Male

Office Type: ☐ Office Cubicle or Open Plan Workstation ☐ Shared Closed Office 2, 3, 4, or more ☐ Individual Closed Office

View: ☐ No View ☐ Seated View

Check the box if the corresponding item / condition is present in the workstation.

Thermal / IAQ Stressors:

Thermal / IAQ

Fan	☐	Diffuser Drafty	☐
Heater	☐	Leaky Wall	☐
Sweater	☐	Radiant Wall	☐
Window AC	☐	Window Sun Blocked	☐
Blocked Diffuser	☐		

Laser Printer	☐	Air Freshener	☐
Inkjet Printer	☐	Cleaning Fluid	☐
Humidifier	☐	Bad Outgassing	☐
Ionizer	☐	Smelly Polluted Air	☐
Printer / Copier	☐	No Dedicated Exhaust	☐
Blocked Diffuser	☐	Kitchen Closed	☐
Air Indicator	☐	Kitchen Open	☐
Adjacent Smoker	☐	Coffee Maker	☐
Recent Cleaning	☐	Microwave	☐

C. Selected COPE questionnaire results

Q2. Overall air quality in your work area:

SOURCE DATA

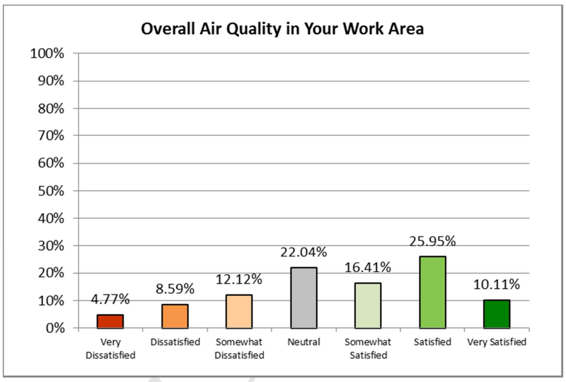
Dissat. (%) Neutral (%) Sat. (%)

	Scale	People	%	People	%
Dissat.(%)	1	50/1048	4.77%	267/1048	25.48%
	2	90/1048	8.59%		
	3	127/1048	12.12%		
Neutral (%)	4	231/1048	22.04%	231/1048	22.04%
Sat.(%)	5	172/1048	16.41%	550/1048	52.48%
	6	272/1048	25.95%		
	7	106/1048	10.11%		

Dissatisfied: 1 to 3 in a 7-point scale from 1 to 7

Neutral: 4 in a 7-point scale from 1 to 7

Satisfied: 5 to 7 in a 7-point scale from 1 to 7



Q14. Air movement in your work area

SOURCE DATA

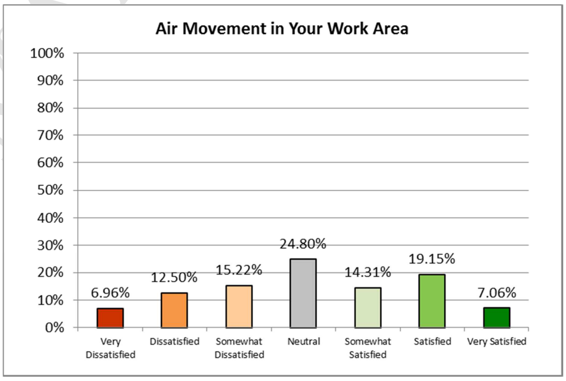
Dissat. (%) Neutral (%) Sat. (%)

	Scale	People	%	People	%
Dissat.(%)	1	83/1197	6.96%	415/1197	34.68%
	2	150/1197	12.50%		
	3	182/1197	15.22%		
Neutral (%)	4	297/1197	24.80%	297/1197	24.80%
Sat.(%)	5	171/1197	14.31%	485/1197	40.52%
	6	229/1197	19.15%		
	7	85/1197	7.06%		

Dissatisfied: 1 to 3 in a 7-point scale from 1 to 7

Neutral: 4 in a 7-point scale from 1 to 7

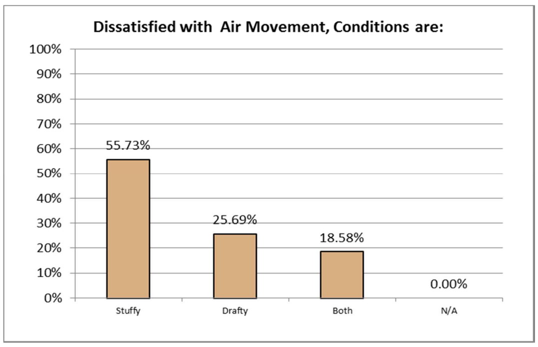
Satisfied: 5 to 7 in a 7-point scale from 1 to 7



If dissatisfied with the air movement, what are the conditions:

SOURCE DATA

Conditions	People	%
Stuffy	141/253	55.73%
Drafty	65/253	25.69%
Both	47/253	18.58%
N/A	0	0%



ACCEPTED MANUSCRIPT