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Examining In Situ Acoustic Conditions for Enhanced Occupant Satisfaction in Contemporary Offices

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Abstract: Indoor acoustic quality is one of the critical indicators for occupants' health, comfort, and productivity in contemporary office environments. Post-occupancy evaluation (POE) is usually employed to examine in situ acoustic measurements to ensure indoor acoustic quality. However, prevailing acoustic performance evaluation does not often consider the technical attributes of building systems (TABS) to holistically investigate the significant correlations between objective acoustic field measurements and subjective POE. As such, this study proposes to cross-examine in situ and perceived acoustic quality indices with TABS to quantify critical factors leading to enhanced occupant satisfaction. Statistical analyses suggest that technical building attributes can significantly influence occupants' acoustic satisfaction compared to sound levels recorded in contemporary offices. For instance, lowering the distributed noise level from above 40% to 2% can lead to an average 21% increase in occupant satisfaction. Ultimately, incorporating environmental measurements with physical building attributes from an occupant-centric perspective can uncover applicable design guidelines for achieving optimal acoustic quality with the highest occupant satisfaction.

Keywords: indoor acoustic quality; acoustic satisfaction; post-occupancy evaluation (POE); indoor environmental quality (IEQ); speech privacy

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1. Introduction

The acoustic conditions of office environments affect user productivity and satisfaction [1]. A good acoustic environment ensures the occupants' psychological and physiological fitness and boosts concentration. In a 2011 laboratory experiment in Sweden, Jahncke et al. found increased performance on memory tasks and reduced tiredness in low-noise (39 dBA) work environments as compared to high-noise (51 dBA) work environments [2,3]. Danielsson and Bodin identified that employees in individual closed offices reported higher health status, such as sleep quality and satisfaction rates, than those in open-plan offices [4]. The types of offices, open or closed, and associated acoustic characteristics, such as privacy and noise disturbance, could have detrimental effects on occupants' wellbeing and impact occupants' job performance and subjective satisfaction.

The detrimental effect of ambient noise on the short-term memory processes was commonly found in a workplace setting [5]. It could lead to plausible causes for reduced efficiency in performing cognitive tasks [6,7]. Previous studies investigated correlations between subjective perception of ambient noise and objective sound spectrum measurement in occupied office environments. The objectives were to quantify the effects of objective acoustic indices on occupants' auditory responses and inform the applicable design and evaluation strategies for a better acoustic environment [8–10]. Ayr et al. further examined the effectiveness of measured noise indices concerning in situ subjective auditory sensations [11]. They found that A-weighted equivalent sound pressure level, L_{Aeq}, performed best in evaluating subjective occupation responses to annoyance, loudness, and dissatisfaction. Similarly, Tang identified that L_{Aeq} best correlated with the auditory sensation of occupants among 14 commonly used noise indices in air-conditioned offices [12].

Several acoustic parameters are often employed to quantify the background noise in buildings, such as electromechanical noise from a heating, ventilation, and air-conditioning (HVAC) system. According to the ASHRAE 2010 measurement protocol, Room Criteria (RC), Noise Criteria (NC), and Balanced Noise Criteria (NCB) are the main factors to be considered [13]. These indicators are determined by comparing the measured background noise to a defined set of sound pressure levels versus frequency curves. Previous studies suggested acoustic satisfaction could be systematically determined by acoustic environmental indices, such as room noise level, acoustic privacy, and personal control (Table 1). The room noise level in the office environment refers to the background noise levels from office equipment noise or co-workers' conversations and is strongly correlated with acoustic satisfaction [14]. Acoustic privacy refers to the reduction in conversation clarity from circulation, support areas, or adjacent offices. It can vary significantly by physical building components, such as partition screens in open-plan offices [15–18]. Personal control of the room noise levels allows occupants to manage unwanted noise and interruptions.

Table 1. Indicators of indoor acoustic quality assessment.

Indices	Goal	Acoustic Quality Indicator	Sources
Noise level	Measure background noise levels and spectrums in each location	Acoustic comfort and satisfaction	[6,14,16,17,19–27]
Acoustic privacy	Support speech privacy—the reduction in conversation clarity from adjacent offices	Speech privacy satisfaction	[2,15–18]
Personal control	Personal control of noise level to support work productivity and comfort	Ability to control unwanted noise and interruptions	[28–30]

According to ASHRAE [13], NCB and RC indicate the presence of rumble excessive low-frequency energy and hiss excessive high-frequency energy as well as noise-induced vibration and evaluate occupant acceptance through a calculation of the Quality Assessment Index (QAI). The QAI is found based on the range of energy-averaged spectral deviations between the measured noise and the RC contour levels. ASHRAE recommends RC/NC/NCB of 30 to 40 dB for open-plan offices and 25 to 35 dB for private offices. The QAI estimates the probable reaction of an occupant when the system design does not produce optimum sound quality. ASHRAE describes a QAI of 5dB or less that corresponds to a generally acceptable condition in all rooms and spaces, regardless of frequencies (Table 2).

Table 2. Summary of Recommended Sound Criteria for Office buildings.

	Indices	Assessment Guidelines	Sources
Acoustic Quality Assessment	Ideal Leq dB (A)	30 (private office) 35 (open-plan office)	[10–12]
	Maximum Leq dB (A)	≤35 (private office) ≤40 (open-plan office without sound masking) ≤35 (open-plan office with sound masking)	
	Room Criteria (RC) Noise Criteria (NC)	25 to 35 (private offices)	
	Balanced Noise Criteria (NCB)	≤40 (open-plan offices)	
	Quality Assessment Index (QAI)	≤5	[10]

To summarize, existing research assesses acoustic quality through measurable noise levels. Albeit useful and informative, these quantitative variables alone are not sufficient to capture actual acoustic comfort perceived by occupants. Additional subjective evaluation through post-occupancy evaluation (POE) can further reveal applicable insights to ensure good indoor environmental quality (IEQ) while maintaining the highest user satisfaction. Previous research demonstrated the applications of POE with IEQ monitoring on thermal, lighting, and air quality to achieve enhanced occupant satisfaction with balanced indoor environmental design [31–33]. Recent acoustic quality assessments in office environments also showed that investigating physical building attributes, such as insulation between spaces, with acoustic quality indexes, such as noise levels and spectrums, can lead to valuable insights for enhanced acoustic satisfaction [34]. However, only limited studies investigated the combined effects of physical attributes of buildings and in situ acoustic conditions on occupant satisfaction. To comprehensively understand the indoor acoustic environment and its impact on subjective acoustic satisfaction, this study concentrated on quantifying critical factors from indoor noise criteria with the added consideration of physical building attributes of office environments leading to the highest occupant acoustic satisfaction. This study utilizes the cross-sectional acoustic satisfaction survey and carries out on-site field measurements across winter, summer, and transitional seasons. The objective is to cross-examine the interaction between objective acoustic factors, including acoustic quality indexes and physical building attributes, and subjective satisfaction evaluation and better understand the extent to which these factors influence acoustic comfort in contemporary office environments. As a result, this study presents applicable acoustic design guidelines for contemporary offices with enhanced occupant acoustic satisfaction.

2. Data Collection and Analysis Methods

The Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon University (CMU) has collected both objective and subjective data on the indoor environmental quality indices, including thermal, air, lighting, and acoustic, at individual workstations in public and private sector buildings. Three different kinds of data were collected to develop a Structured Query Language (SQL) database, consisting of the workstation's indoor environment quality (IEQ) measurements, technical attributes of building systems, and occupant satisfaction surveys [35]. This database provides a rich foundation to investigate critical correlations between the measured indoor environmental quality, the technical attributes of the building systems, and occupants' satisfaction [36].

In addition to the critical factors leading to optimal thermal, air, and visual conditions [31–33], findings on the acoustic field data collected between 2003 and 2014 from 64 buildings are presented in this paper with in-depth statistical analysis. A total of 1340 workstations, consisting of 31% in closed offices and 69% in open-plan offices, were investigated. Buildings include both federal and private sector offices of less than 500 m^2 in finances, sales, and marketing to enable cross-sectional analyses. The variable sampling rate of spot measurements was an average of 30% of the total office workstations per floor, or a minimum of 15 workstations for a small workgroup, to cover representative workstation variables. Sampling considerations include the workstation locations (perimeter or core), orientation (north, south, east, or west), and office types (open or closed).

2.1. Field Data Collection

In this study, acoustic field measurements followed ASHRAE performance measurement protocols with Level 2 intermediate performance [13]. Table 3 illustrates three levels of measurement protocols in the field study. In this study, the objective of using the Level 2 measurement is to identify acoustic annoyance that would affect productivity, speech and telephone communication, listening conditions, and privacy. As a class 1 sound measurement, this research utilized a Brüel & Kjær Sound Level Meter 2250-L [37] and the utility software for recording and processing background noise and reverberation time in a room. The instrument was set up for the participants' workstations at approximately 0.75 m from the ground (Figure 1).

Table 3. Performance Measurement Protocols for Commercial Buildings by ASHRAE 2010.

	Level 1—Basic Performance Method	**Level 2—Intermediate Performance Method**	**Level 3—Advanced Performance Method**
Objectives	• Simple evaluation of background noise	• General assessment of speech communication issues (e.g., speech, listening conditions) • Comparison of sound quality by room use	• Accurate assessment of speech privacy, speech communication, and isolation from intruding noise • Special purpose room uses
Evaluation	• Occupant survey • Background noise	• Occupant survey • Background noise • Reverberation times	• Occupant survey • Background noise • Reverberation times
Metrics	• A-weighted sound pressure level (Leq in dBA)	• Room Criterion (RC) • Noise Criterion (NC) • Balanced Noise Criterion (NCB)	• Speech privacy: Privacy Index (PI) • Speech intelligibility: Speech Transmission Index (STI) • Acoustic separation: Noise Isolation Class (NIC)
Instrumentation	• Occupant survey • A handheld Type 1 portable sound meter	• Occupant survey • A handheld Type 1 portable sound meter • Sound source, amplifier	• Occupant survey • A handheld Type 1 portable sound meter • Sound source, amplifier
Test Condition	• Conducted with the room vacated by its normal occupants • All non-HVAC-related sound-producing equipment (computers, radios, etc.) should be turned off during the measurements	• Conducted with the room vacated by its normal occupants • All non-HVAC-related sound-producing equipment (computers, radios, etc.) should be turned off during the measurements	• Conducted with the room vacated by its normal occupants • All non-HVAC-related sound-producing equipment (computers, radios, etc.) should be turned off during the measurements
Recommended Levels	• A-weighted sound level *Office buildings* / *Ideal Leq (dBA)* / *Max. Leq (dBA)* Private offices / 30 / 40 Conference room / 30 / 40 Teleconference room / 25 / 30 Open-plan office / 35 / 45 Open-plan office / 35 / 40 Corridors and lobbies / 40 / 50	• RC/NC/NCB *Office buildings* / *Ideal Leq (dBA)* / *Max. Leq (dBA)* Private offices / 25–35 / 40 Conference room / 25–35 / 40 Teleconference room / ≤25 / 30 Open-plan office / ≤40 / 45 Open-plan office / ≤35 / 40 Corridors and lobbies / 40–45 / 50	• Speech privacy *Privacy Index (PI)* Confidential speech privacy / 100–95% Non-intrusive (normal, open-plan office) speech privacy / 95–80% Poor speech privacy / 80–60% Complete lack of privacy / <60% • Speech intelligibility *Speech Transmission Index (STI)* Excellent / 1.0–0.75 Good / 0.75–0.60 Fair / 0.60–0.45 Poor / <0.45

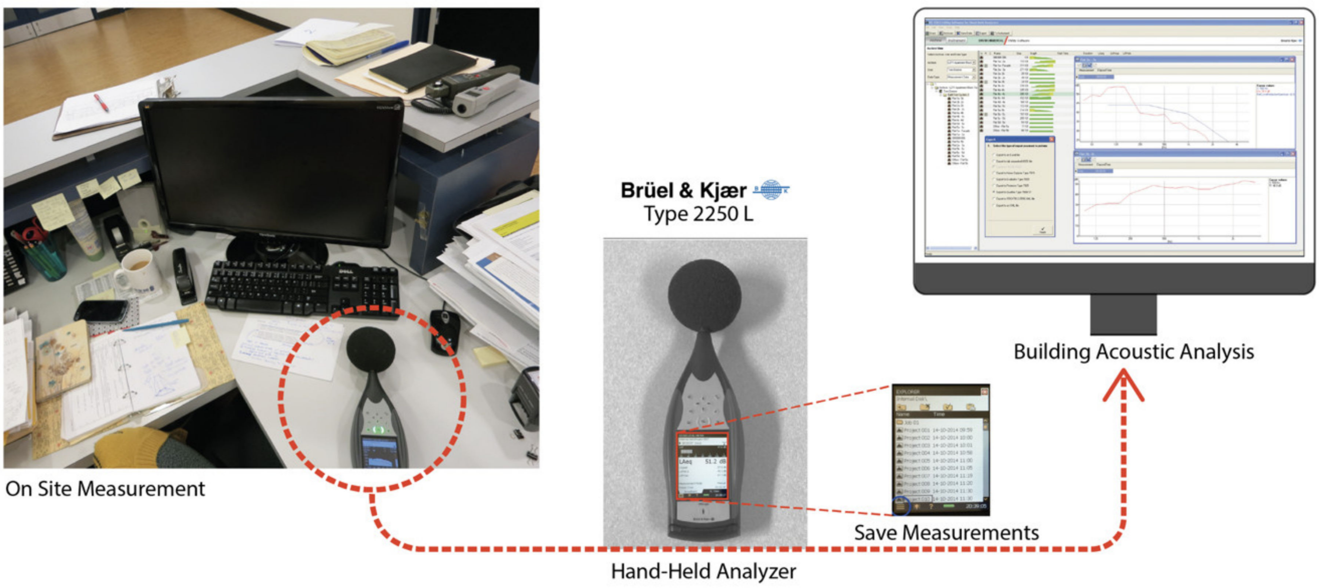


Figure 1. Class 1 sound measurement in the field using the handheld sound level meter 2250-L with microphone type 4950.

In addition to acoustic field measurements, the CBPD developed expert walkthrough methods to record technical attributes of building systems (TABS). The objective is to quantify the impacts of critical physical attributes of the building and workplace on acoustic conditions and individual/organization performance. Appendix A shows the TABS matrix for acoustic quality evaluation, and Appendix B shows workstation contextual data. In total, this study considers eleven physical attributes from six building components, including ceilings, floors, walls, workstations, partitions, and HVAC.

In the Cost-effective Open-Plan Environment (COPE) questionnaires originally developed by the National Research Council Canada [38], participants were asked to respond to an acoustic satisfaction survey on (1) background noise, (2) distractions from other people, (3) noise from people's conversation, and (4) acoustic privacy for conversations. This survey was distributed via paper or tablet device to employees who occupied the workstations following the sampling strategies mentioned above. Each participant was provided with essential project information and asked to give his/her consent before undertaking the spot measurements and the user satisfaction survey. Through qualitative statistical analyses, this survey aims to understand the impacts of in situ environmental and physical conditions on occupants' satisfaction.

Table 4 summarizes three datasets considered for indoor acoustic quality analysis from the original 1340 workstations in 64 buildings. In total, twenty variables were first collected for NEAT IEQ measurements (n = 5), TABS (n = 11), and COPE (n = 4). After data screening with the correlation matrix, thirteen variables, including four IEQ measurements, seven TABS, and two COPE questions, were filtered for further correlation analyses. Four workstation noise measurement criteria selected are Sound level (dBA), Noise Criteria (NC), Balanced Noise Criteria (NCB), and Room Criteria (RC). Seven technical attributes of building systems (TABS) include "Ceiling quality", "Floor quality", "Workstation size", "Partition height", "Partition sides", "Distributed noise", and "Sound masking". Lastly, two COPE user satisfaction questions are (1) the amount of background noise from mechanical or office equipment you hear at your workstation and (2) the frequency of distractions from other people. These thirteen variables serve as the basis for examining correlations among user satisfaction, the technical attributes of building systems, and the workstation's IEQ measurements.

Table 4. This is a table. Tables should be placed in the Acoustic quality datasets considered for each workstation.

	NEAT **IEQ Measurements**	**TABS** **Technical Attributes of Building Systems**	**COPE** **User Satisfaction Survey**
Acoustic Quality Assessment	• **Sound level (dBA) *** • **Noise Criteria (NC) *** • **Balanced Noise Criteria (NCB) *** • **Room Criteria (RC) *** • Quality Assessment Index (QAI)	• **Ceiling quality *** • **Floor quality *** • **Workstation size *** • **Partition height *** • **Partition sides *** • Partition thickness and quality • Size/density of workstation • **Distributed noise *** • HVAC noise • **Sound masking *** • System furniture quality	Q. **Amount of background noise *** Q.**Frequency of distractions from other people *** Q. Amount of noise from other people's conversations Q. Level of acoustic privacy for conversations in your work area 7-point Likert Scale: Very Dissatisfied/Dissatisfied /Somewhat Dissatisfied/Neutral /Somewhat Satisfied/Satisfied /Very Satisfied

* Selected for correlation analysis.

2.2. Data Analysis

Table 5 presents the demographic information in this acoustic quality study. There are 531 male and 519 female participants between the age of 18 and 69. The total received responses of 1050 differed from the total IEQ measurements as the demographic question was not mandatory.

Table 5. Participant demographic information.

Age	Female	Male	Total
20–29	116	132	248 (24%)
30–39	158	136	294 (28%)
40–49	124	120	244 (23%)
50–59	107	98	205 (19%)
60+	15	26	41 (4%)
Unidentified	11	7	19 (2%)
Total	531 (51%)	519 (49%)	1050

Given the valid response from 1037 occupants in sixty-four office buildings, 46% of occupants responded "satisfied", and 34% of occupants reported "dissatisfied" with background noise from the mechanical or office equipment in the work area (Figure 2a). The average satisfaction level is 0.25, which falls between "Neutral" and "Somewhat Satisfied" on a 7-point Likert scale. For frequency of distractions from others (Figure 2b), only 39% of occupants responded as satisfied. The average satisfaction level is −0.01, around "Neutral" on a 7-point Likert scale. These results suggest the quality of the acoustic environment in contemporary office environments could still be improved.

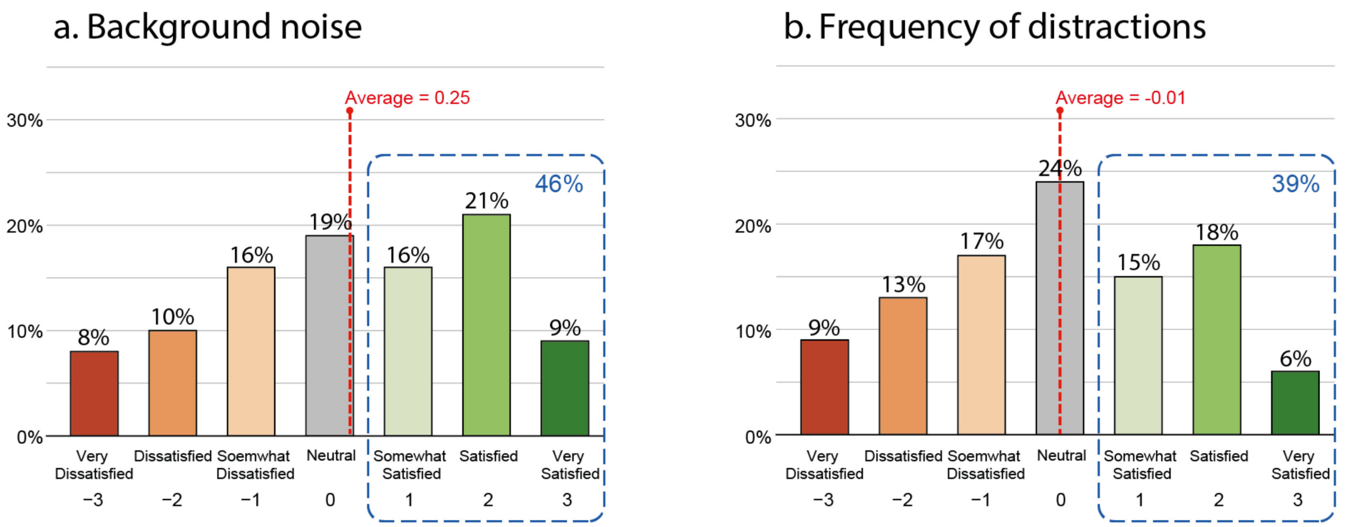


Figure 2. Acoustic satisfaction survey results: (**a**) Background noise from mechanical or office equipment you hear in your work area; (**b**) frequency of distractions from other people, from 1037 workstations in 64 buildings.

This study developed four statistical models to test the correlation between objective acoustic measurements, technical building attributes, and subjective acoustic satisfaction, as shown in Table 6. The first three models examine the correlation between pairs of individual components, and the fourth one considers the combined effect of technical building attributes and workstation acoustic measurements on occupant satisfaction. For each correlation test, this study employed two-sample *t*-tests for binary variables and one-way ANOVA for multi-valued variables. Further chi-square tests and contingency analyses were then performed to determine the significant difference between variables influencing user satisfaction.

2.2.1. Workstation Acoustic Quality Measurements versus User Satisfaction

First, the correlation between workstation acoustic quality measurements and user satisfaction was tested. Contextual variables, including gender, perimeter versus core workstation location, and open-plan versus closed office type, were also tested for correlation with acoustic satisfaction. In this correlation test, two satisfaction responses in the COPE questionnaires (including the amount of background noise from mechanical or office equipment the occupant hears at his/her work area and frequency of distractions from other people) and four IEQ measurements assessed by the NEAT instrument were analyzed using ordinary least squares and ordered logistic fit.

Table 6. Analysis models with objectives.

Model	Objective	Diagram
Model 1	Correlation test between workstation acoustic quality measurements (NEAT) and user satisfaction (COPE)	NEAT → COPE
Model 2	Correlation test between technical attributes of building systems (TABS) and user satisfaction (COPE)	TABS → COPE
Model 3	Correlation test between technical attributes of building systems (TABS) and workstation acoustic quality measurements (NEAT)	TABS → NEAT
Model 4	Correlation test between the combination of technical attributes of building systems (TABS) and workstation acoustic quality measurements (NEAT) and user satisfaction (COPE)	TABS + NEAT → COPE

In Table 7, acoustic satisfaction with "Amount of background noise from mechanical or office equipment you hear at your work area" is found significantly correlated with office type ($p \leq 0.01$). The occupants of closed offices show higher satisfaction with both questions. The analysis result showed that the measured acoustic variables, including Sound level, Room Criteria, Noise Criteria, and Balanced Noise Criteria, are not significantly correlated with user satisfaction with background noise in the work area ($p > 0.05$).

Table 7. Correlation analysis between NEAT acoustic quality measurements and the acoustic satisfaction with background noise (n = 902).

Acoustic Quality	Code	Variables	Coefficient	*p*-Value
NEAT	C-1	Female–Male	−0.27	0.425
	C-2	Perimeter–Core	−0.27	0.443
	C-3	Open–Closed	1.14	0.009 **
	NA-1	Sound Level	0.027	0.157
	NA-2	Room Criteria	0.136	0.975
	NA-3	Noise Criteria	−0.114	0.67
	NA-4	Balanced Noise Criteria	−0.136	0.583

** $p \leq 0.01$.

2.2.2. Technical Attributes of Building Systems versus User Satisfaction

The correlation analysis between technical attributes of building systems and user satisfaction was conducted. In this test, the correlations between seven physical building attributes recorded in TABS, three contextual variables, and two user satisfaction questions in the COPE questionnaires (the amount of background noise from mechanical or office equipment the occupant hears at his/her work area and frequency of distractions from other people) were analyzed using ordinary least squares and ordered logistic fit.

User satisfaction with background noise and frequency of distraction is significantly correlated with four physical attributes, including the size of the workstation ($p \leq 0.001$), partition height ($p \leq 0.05$), partition sides ($p \leq 0.01$), and distributed noise ($p \leq 0.01$), as shown in Table 8. In this test, four key findings were identified for further study:

- Bigger workstations can increase user satisfaction ($p \leq 0.001$);
- higher partition height can increase user satisfaction by 0.68 points compared to low or medium height partition ($p \leq 0.05$);
- multiple partition sides result in increased user satisfaction ($p \leq 0.01$);

- lower distributed noise can increase user satisfaction ($p \leq 0.01$).

Table 8. Correlation analysis between TABS and COPE satisfaction with background noise ($n = 498$).

Acoustic Quality	Code	Variables	Coefficient	*p*-Value
TABS	C-1	Female–Male	−0.27	0.305
	C-2	Perimeter–Core	−0.27	0.035 *
	C-3	Open–Closed	1.14	0.001 ***
	TA-1	Ceiling quality		
	TA-1-1	Hard surface vs. Floating acoustic elements	0.34	0.683
	TA-1-2	Hard surface vs. Acoustic plaster	0.25	0.602
	TA-1-3	Hard surface vs. Metal or wood slats w/fiber glass	0.14	0.697
	TA-2	Floor quality		
	TA-2-1	Hard surface vs. Carpet in circulation areas	0.47	0.072
	TA-2-2	Hard surface vs. Thin carpet	0.43	0.16
	TA-2-3	Hard surface vs. Thick carpet w/padding	0.07	0.865
	TA-3	Size of workstation		
	TA-3-1	<36 sqft vs. <50 sqft	0.007	0.991
	TA-3-2	<36 sqft vs. <64 sqft	1.85	0.001 ***
	TA-3-3	<36 sqft vs. <100 sqft	0.79	0.045 *
	TA-3-4	<36 sqft vs. <120 sqft	1.03	0.062
	TA-4	Partition height: Low (≤120 cm) vs. high (>120)	0.68	0.033 *
	TA-5	Partition sides		
	TA-5-1	None vs. 1 side	0.42	0.237
	TA-5-2	None vs. 2–3 sides	0.8	0.004 **
	TA-5-3	None vs. 3.5 to 4 sides	0.62	0.067
	TA-6	Distributed noise		
	TA-6-1	>40% vs. 10–40%	0.45	0.195
	TA-6-2	>40% vs. 2–10%	0.6	0.057
	TA-6-3	>40% vs. <2%	1.02	0.003 **
	TA-7	Sound masking	0.44	0.372

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

2.2.3. Technical Attributes of Building Systems versus Workstation Acoustic Quality Measurements

The correlation between technical attributes of building systems and workstation IEQ measurements was assessed. Contextual variables such as gender, perimeter vs core workstation location, and open-plan workstations versus closed offices were also tested for correlation with workstation IEQ measurements. In this test, the correlations between the four IEQ measurements assessed by the NEAT instrument and seven physical building attributes investigated in the TABS records were analyzed using ordinary least squares and ordered logistic fit.

In Table 9, two technical attributes of the building systems showed significant correlations with workstation acoustic measurements:

- Workstations with 3.5 to 4 sides revealed an average of 6.56 dB lower Noise Criteria (NC) level than those without partitions ($p \leq 0.05$).
- Floors with less than 2% of the workstations near distributed noise sources showed, on average, 9.87 dB lower Noise Criteria (NC) level than floors with more than 40% of the workstations near distributed noise sources ($p \leq 0.01$). This would suggest that printer/copier and kitchen amenities be removed from circulation and empty workstations to reduce noise.

2.2.4. The Combination of Technical Attributes of Building Systems and Workstation IEQ Measurements versus User Satisfaction

The correlation test between a total of eleven variables (seven physical attributes investigated in the TABS record and four workstation IEQ measurements assessed by the NEAT instrument) was analyzed using ordinary least squares and ordered logistic fit relative to two user satisfaction areas investigated in the COPE questionnaires (amount of background noise from mechanical or office equipment the occupant hears at his/her work area and frequency of distractions from other people).

Table 9. Correlation analysis between TABS and Noise Criteria ($n = 498$).

Acoustic Quality	Code	Variables	Coefficient	p-Value
TABS	C-1	Female–Male	0.28	0.911
	C-2	Perimeter–Core	−0.32	0.917
	C-3	Open–Closed	−4.09	0.238
	TA-1	Ceiling quality		
	TA-1-1	Hard surface vs. Floating acoustic elements	−10.9	0.273
	TA-1-2	Hard surface vs. Acoustic plaster	−4.55	0.329
	TA-1-3	Hard surface vs. Metal or wood slats w/fiber glass	−0.81	0.909
	TA-2	Floor quality		
	TA-2-1	Hard surface vs. Carpet in circulation areas	−0.51	0.915
	TA-2-2	Hard surface vs. Thin carpet	5.7	0.486
	TA-2-3	Hard surface vs. Thick carpet w/padding	−7.38	0.283
	TA-3	Size of workstation		
	TA-3-1	<36 sqft vs. <50 sqft	8.37	0.33
	TA-3-2	<36 sqft vs. <64 sqft	1.09	0.909
	TA-3-3	<36 sqft vs. <100 sqft	1.47	0.671
	TA-3-4	<36 sqft vs. <120 sqft	1.24	0.955
	TA-4	Partition height: Low (≤120 cm) vs. high (>120)	−2.87	0.452
	TA-5	Partition sides		
	TA-5-1	None vs. 1 side	−3.78	0.593
	TA-5-2	None vs. 2–3 sides	−6.87	0.247
	TA-5-3	None vs. 3.5 to 4 sides	−6.56	0.038 *
	TA-6	Distributed noise		
	TA-6-1	>40% vs. 10–40%	4.42	0.326
	TA-6-2	>40% vs. 2–10%	4.7	0.367
	TA-6-3	>40% vs. <2%	−9.87	0.005 **
	TA-7	Sound masking	−4.06	0.776

* $p \leq 0.05$, ** $p \leq 0.01$.

The statistical results in Table 10 illustrate positive increases in user satisfaction based on a 7-point Likert scale. In particular, "Size of workstation" ($p \leq 0.01$) and "Distributed noise" ($p \leq 0.01$) were found to be significantly correlated with user satisfaction with the background noise.

- The occupants who have bigger workstations showed higher satisfaction ($p \leq 0.01$).
- Partition sides result in increased user satisfaction ($p \leq 0.01$).
- Less distributed noise (less than 2% of distributed noise) can increase user satisfaction ($p \leq 0.01$).

Table 10. Correlation analysis between TABS, Noise Criteria, and COPE satisfaction with background noise ($n = 498$).

Acoustic Quality	Code	Variables	Coefficient	p-Value
TABS + NEAT	C-1	Female–Male	−0.44	0.517
	C-2	Perimeter–Core	−1.38	0.127
	C-3	Open–Closed	1.89	0.066
	TA-1	Ceiling quality		
	TA-1-1	Hard surface vs. Floating acoustic elements	3.22	0.427
	TA-1-2	Hard surface vs. Acoustic plaster	−0.35	0.894
	TA-1-3	Hard surface vs. Metal or wood slats w/fiber glass	0.02	0.992

Table 10. *Cont.*

Acoustic Quality	Code	Variables	Coefficient	*p*-Value
TABS + NEAT	C-1	Female–Male	−0.44	0.517
	TA-2	Floor quality		
	TA-2-1	Hard surface vs. Carpet in circulation areas	1.2	0.581
	TA-2-2	Hard surface vs. Thin carpet	1.46	0.544
	TA-2-3	Hard surface vs. Thick carpet w/padding	1.84	0.49
	TA-3	Size of workstation		
	TA-3-1	< 36 sqft vs. < 50 sqft	0.27	0.779
	TA-3-2	< 36 sqft vs. < 64 sqft	1.8	0.064
	TA-3-3	< 36 sqft vs. < 100 sqft	1.28	0.05 *
	TA-3-4	< 36 sqft vs. < 120 sqft	1.59	0.007 **
	TA-4	Partition height: Low (≤120 cm) vs. high (>120)	0.57	0.765 *
	TA-5	Partition sides		
	TA-5-1	None vs. 1 side	1.82	0.412
	TA-5-2	None vs. 2–3 sides	1.97	0.207
	TA-5-3	None vs. 3.5 to 4 sides	0.1	0.07
	TA-6	Distributed noise		
	TA-6-1	>40% vs. 10–40%	0.62	0.263
	TA-6-2	>40% vs. 2–10%	1.27	0.099
	TA-6-3	>40% vs. <2%	2.05	0.004 **
	TA-7	Sound masking	0.37	0.905
	NA-1	Sound level	0.045	0.275
	NA-2	Room Criteria	0.031	0.915
	NA-3	Noise Criteria	0.59	0.1
	NA-4	Balanced Noise Criteria	−0.56	0.297

* $p \leq 0.05$, ** $p \leq 0.01$.

3. Results and Discussions

Four field measurements, including room Sound level, Room Criteria (RC), Noise Criteria (NC), and Balanced Noise Criteria (NCB), were used to capture the acoustic quality of each workstation. As shown in Figure 3, the statistical analyses reveal that there were no significant correlations between measured NC levels and two user satisfaction questions, including background level in the work area ($p > 0.05$, $n = 574$) and frequency of distractions from others ($p > 0.05$, $n = 582$). Most NC levels were above the recommended threshold (40 dBA), which explains the resulting unsatisfactory acoustic responses with an average neutral to a somewhat satisfactory level, as discussed above in Figure 2.

3.1. Bigger Workstation Leads to Greater Satisfaction

Acoustic satisfaction with background noise and frequency of distraction from others would increase when the workstation size is bigger in open-plan offices. The size of a workstation is defined as the net square feet (sqft) of a workstation. The TABS for the size of a workstation was differentiated into five categories. Table 11 shows the distribution in workstation sizes for 570 questionnaire respondents in open-plan offices from 64 buildings.

Acoustic satisfaction with control of background noise in the work area and the frequency of distraction from others increased as the workstation size increased in open-plan workstations. The relation is highly and positively correlated in both background noise satisfaction ($p < 0.0001$, $n = 570$) and frequency of distraction ($p < 0.05$, $n = 570$). On average, over 60% of occupants were satisfied with the background noise level when the workstation size was larger than 120 sqft, compared to less than 40% when the workstation size was smaller than 50 sqft (Figure 4). This finding suggests that the size of a workstation is a useful design factor for achieving an office environment with satisfactory acoustic conditions.

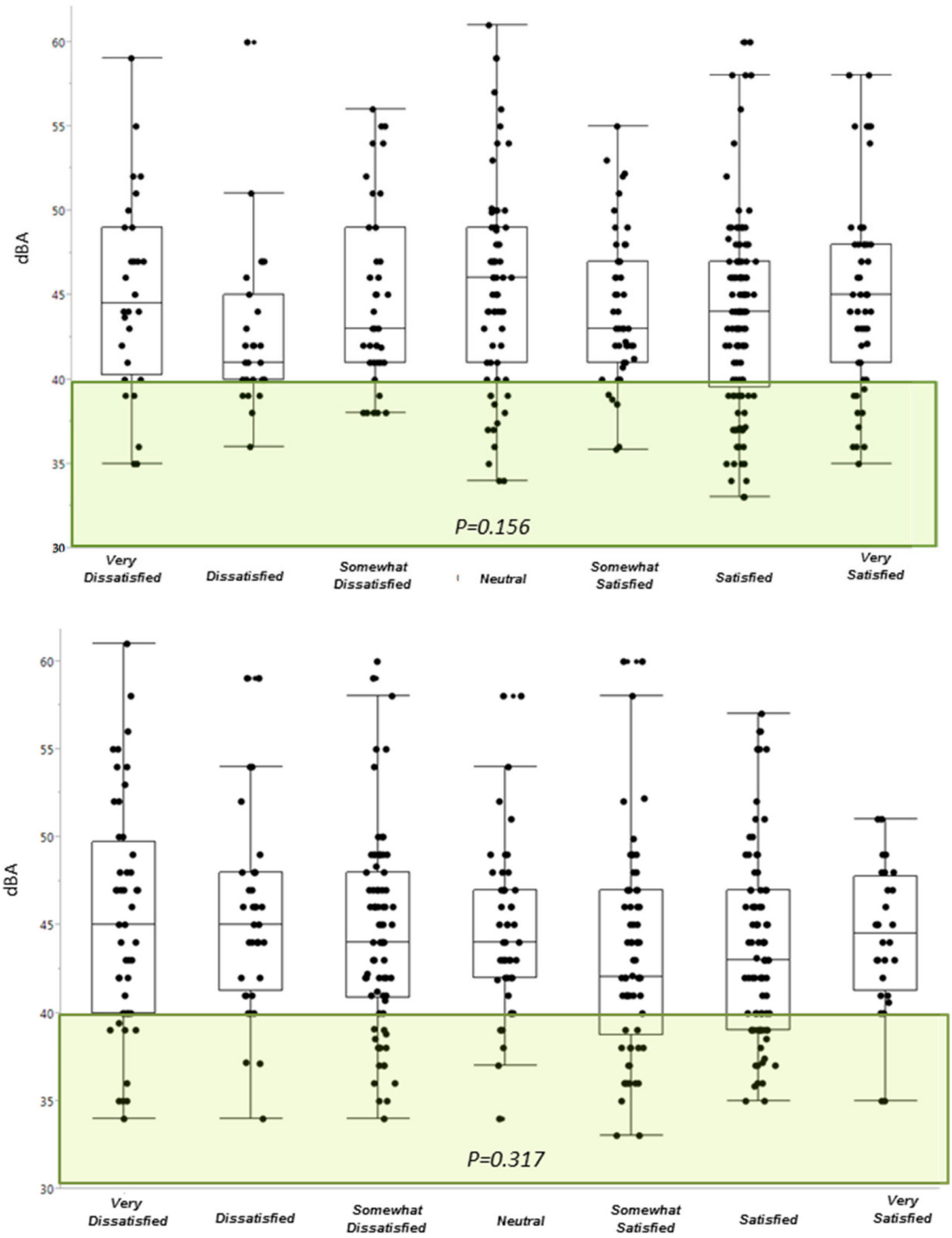
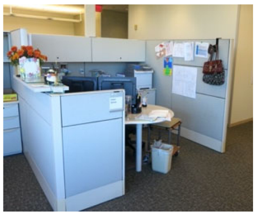
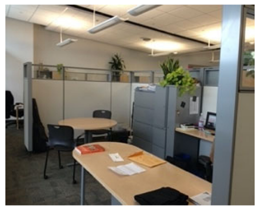


Figure 3. (**Top**) Noise Criteria by user satisfaction with background noise; (**bottom**) Noise Criteria by user satisfaction with frequency of distraction from other people.

Table 11. Distribution in the Size of the Workstation for 570 Questionnaire respondents in open-plan workstations.

Size of Workstation				
				
≤3.3 m^2 (36 ft^2)	4.5 m^2 (50 ft^2)	6 m^2 (64 ft^2)	9.5 m^2 (100 ft^2)	≥ 12 m^2 (120 ft^2)
n = 42 (7%)	n = 227 (40%)	n = 167 (29%)	n = 114 (20%)	n = 20 (4%)

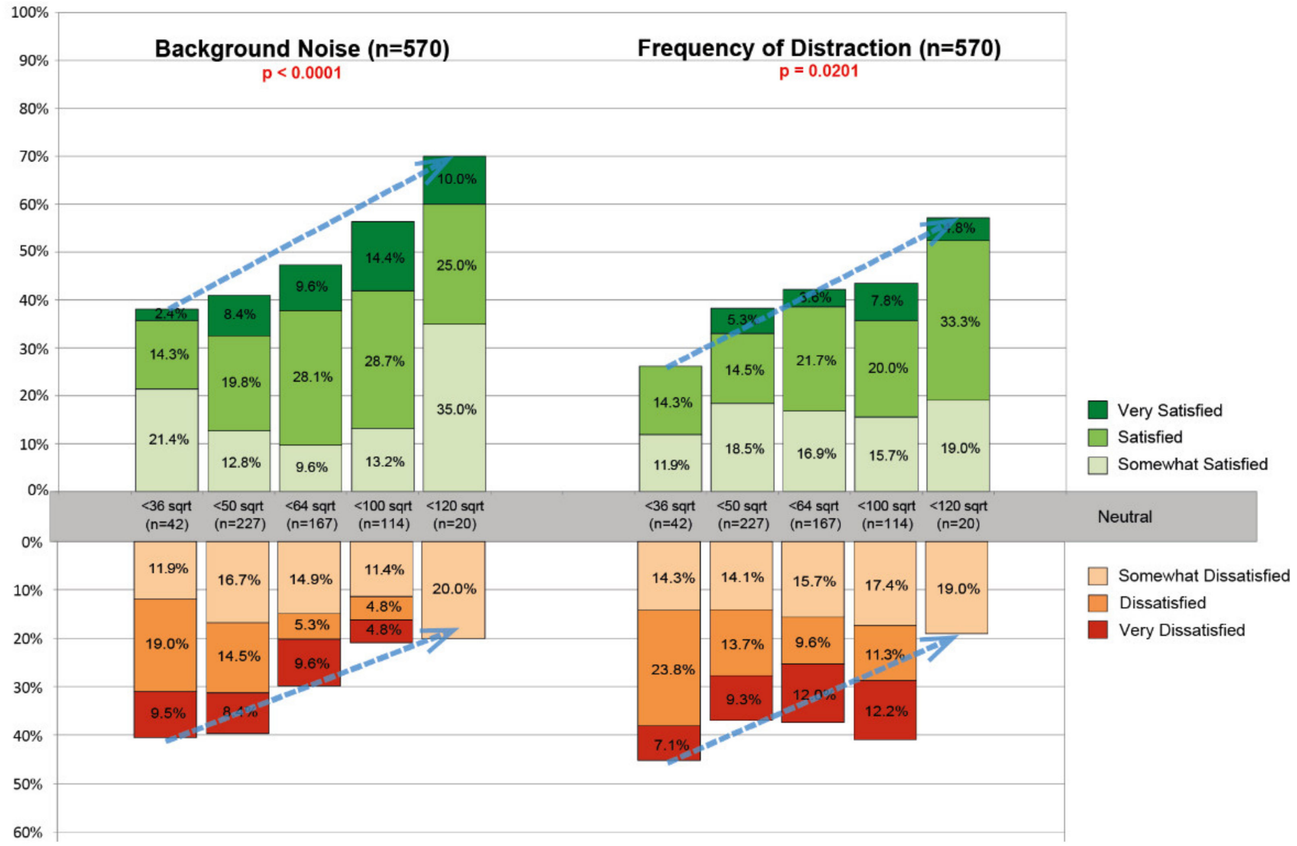


Figure 4. Acoustic satisfaction by Size of workstation: Background noise (n = 570) and frequency of distraction (n = 570) in open-plan workstations.

3.2. More Partition Sides Contribute to Increased Acoustic Satisfaction

Acoustic satisfaction with the management of background noise and frequency of distraction from others increases with more partition sides. The partition side refers to the number of partitions surrounding the workstation. The TABS for partition sides was differentiated into four categories, as shown in Table 12. Among 559 respondents in 64 buildings, 27% had one side partition, 37% of the workstations were surrounded by partitions on 2–3 sides, and 13% had partitions on 3.5–4 sides, ostensibly nearly "closed" office workstations.

Acoustic satisfaction with managing background noise and frequency of distraction from others increased with more partition sides in the open-plan office. Figure 5 illustrates the positive correlation in satisfaction with both background noise level ($p = 0.0127$, $n = 559$) and frequency of distraction in their work area ($p = 0.0001$, $n = 559$). On average, workstations with 3.5 to 4 sides partition had the highest satisfaction (61%), followed by 2–3 sides (52%), one side (51%), and no partition (36%) in descending order against background noise. The same trend was also identified in the frequency of distraction in their work area.

Table 12. Distribution in Partition Sides for 559 Questionnaire respondents in open-plan workstations.

Number of Partition Side(s)			
			
No partition	1 side	2–3 sides	3.5 to 4 sides
$n = 75$ (23%)	$n = 153$ (27%)	$n = 205$ (37%)	$n = 126$ (13%)

Figure 5. Acoustic satisfaction by partition sides: Background noise ($n = 559$) and frequency of distraction ($n = 559$) in open-plan offices.

3.3. Higher Partitions Lead to Higher Acoustic Satisfaction and Lower Noise Criteria

Higher partitions in the open-plan offices can increase acoustic satisfaction by managing background noise and frequency of distraction. In this study, the partition heights were aggregated into low or medium height and high partitions, behind which occupants cannot be seen. Among 493 respondents in open-plan offices, 55% of workstations had low or medium height partitions, and 45% had high partitions, as illustrated in Table 13.

The correlations between partition height with acoustic satisfaction of background noise (p = 0.0312, n = 493) and frequency of distraction from others (p = 0.0222, n = 493) were found statistically significant. On average, workstations with high partitions showed 8% higher satisfaction for two acoustic quality indexes—background noise and frequency of distraction from others—than those with low or medium partitions (Figure 6). This observed trend suggests a practical application of the higher partition to ensure better acoustic satisfaction.

Table 13. Distribution of partition height in open-plan offices (n = 493).

Partition Height	
	
Low or medium height partition	High partition
Height $\leq$ 120 cm (48 inch)	Height > 120 cm (48 inch)
n = 270 (55%)	n = 223 (45%)

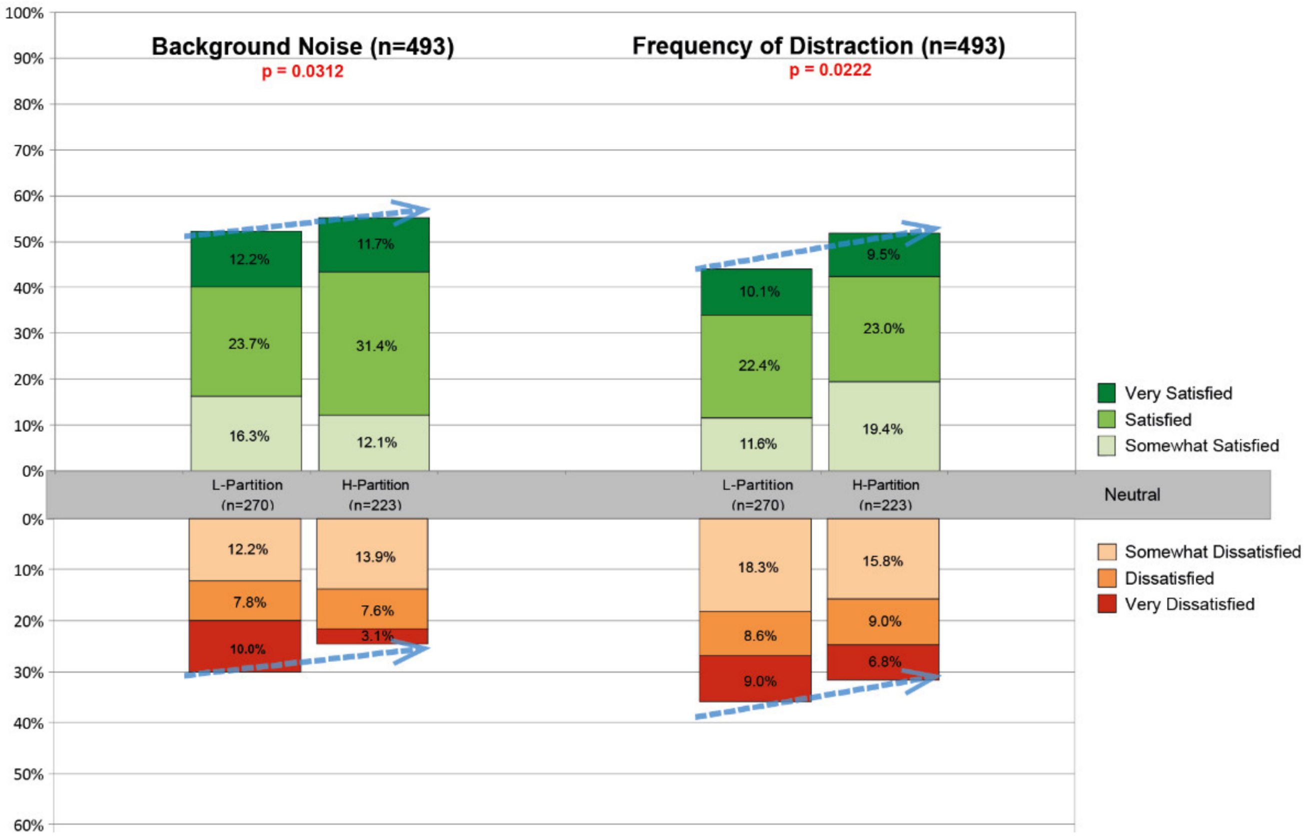


Figure 6. Acoustic satisfaction by partition height: Background noise and frequency of distraction.

3.4. Management of Distributed Noise Sources Increases Acoustic Satisfaction

Distributed noise sources include printers, coffee, and adjacent kitchens, which affect acoustic satisfaction with both background noise and frequency of distraction from others. The TABS for distributed noise level was differentiated by the percentage (%) of workstations on their floor within 20 feet from noise distraction sources. Four categories utilized in this study are shown in Table 14.

Table 14. Acoustic Quality TABS: Distributed noise level.

Distributed Noise Level			
>40% distributed noise	10–40% distributed noise	2–10% distributed noise	<2% distributed noise

Among 485 respondents, 27% of the workstations studied were in the most distracting open-plan set up with >40% of distributed noise sources. Fourteen percent of the workstations were in settings with few (less than 2%) distributed noise sources, as shown in Figure 7.

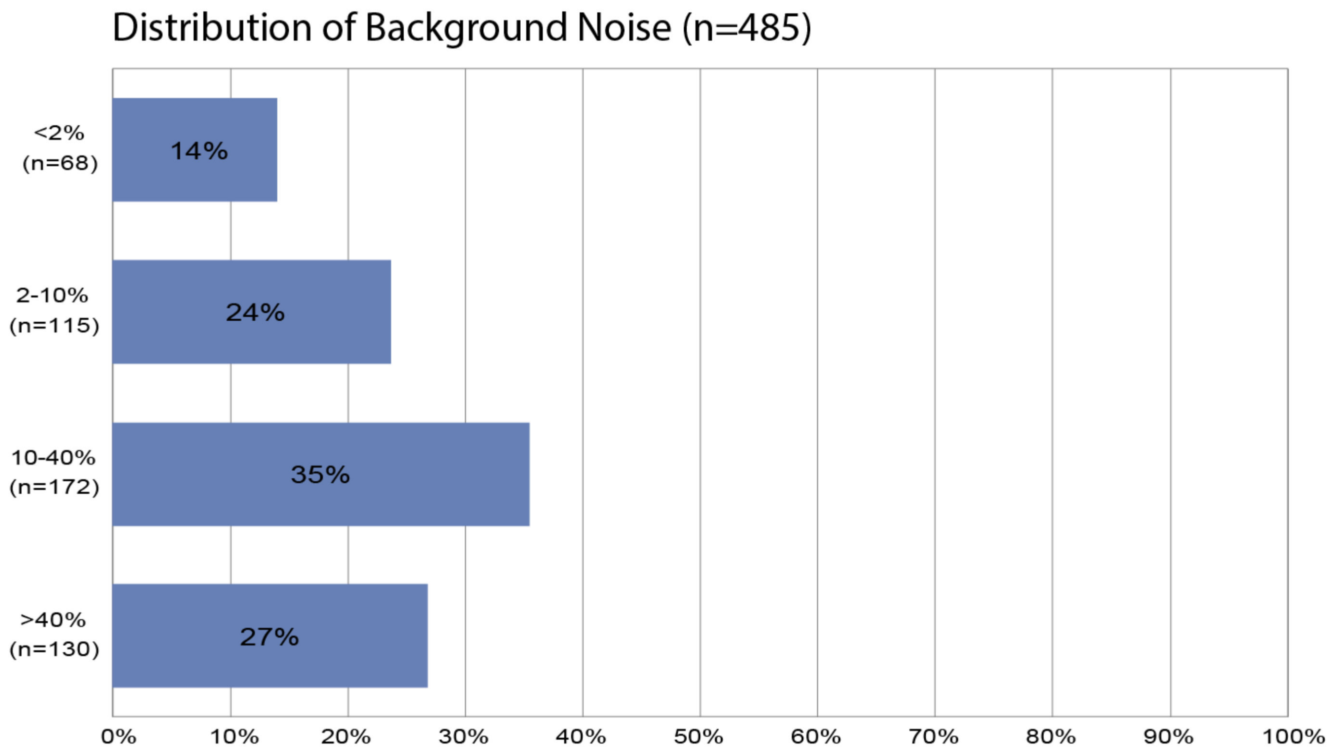


Figure 7. Distribution in distributed noise level for 485 questionnaire respondents.

Acoustic satisfaction increased as distributed noise sources were reduced in the open-plan offices (Figure 8). The correlation is highly and positively correlated with both background noise (p = 0.0021, n = 485) and frequency of distribution (p = 0.0037, n = 485). The observed trend shows that acoustic satisfaction would increase as the distributed noise level decreased. On average, 57% of occupants were satisfied with less than 2% of the distributed noise level, while only 36% of occupants were satisfied with their acoustic quality when the workstation had more than 40% of the noise distribution. A partitioned space with less than 2% of distributed noise can increase user satisfaction by up to 21% on average. Other noise sources such as printers and coffee and water machines identified through the survey should be relocated to a dedicated room to enhance occupant satisfaction.

Figure 8. Acoustic satisfaction by percent of distributed noise sources: Background noise and frequency of distraction.

4. Conclusions

In this study, people show a favorable satisfaction level of 0.25 points on a 7-point Likert scale on their acoustic conditions. Four physical building attributes are found to be statistically significant to acoustic satisfaction. Among these variables, the size of the workstation is the most critical factor, followed by the distributed noise level and space partition applications in open-plan offices. These findings demonstrate the effect of holistically considering physical building attributes in quantifying the perceived acoustic satisfaction. To summarize, a bigger workstation size, multi-side higher partitions, and low noise distribution can be practical acoustic design guidelines to be adopted alongside active noise reduction measures, such as noise-absorbing insulation.

Due to the nature of field measurements, the conclusions were based on data collected on-site as opposed to controlled experiments and derived from an existing mixed-quality building stock. The NEAT short-term spot measurements were limited to one season per building. Further, data collection for building system technical attributes depended on the interpretations of experts in the field. A more robust and systematic way of collecting building system information would be required, e.g., retrieving from digital building information models or databases, to further improve the accurate data collection and management.

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Appendix A. Selected Technical Attributes of Building Systems: Acoustic Quality

Acoustic TABS: Baseline Physical Attributes/ Quality Differences

by floor or by zone, circle the existing physical attributes affecting user satisfaction and field measurements;
if multiple conditions exist, add % of workstations affected by each; add real specifications if available at end of each row

#______ open workstations, #_____ closed workstations; #______ open meeting spaces, #______ closed meeting:
#_____open copy _____ kitchen, #_____ closed copy _____ kitchen

Ceiling Height ____ ft & Ceiling quality	Hard surface or open w/out acoustic material	floating acoustic elements	painted acoustic tile	acoustic plaster	metal or wood slats with fiberglass	mineral acoustic tile,	fiberglass acoustic tile
Floor quality	Hard Surface throughout	Carpet in circulation areas		Thin Carpet throughout			Thick carpet w/ padding
Open plan partition thickness & quality		1 inch	1.5 inch	2 inch	2.5 inch	3 inch	4 inch
		Empty inside		Insulation inside			Insulation and foil/board inside
		Hard surface		Perforated surface		Fabric surface	
Partition height inches & number of sides/workstation (note % of each)	No partitions	1 side (heights?____)	2 sides (heights?____)	3 sides (heights?____)	3.5 sides (heights?____)		4 sides w/door (heights?____)
Overhead bins # of sides		0	1	2	3		
closed office/rooms wall quality		Relocatable wall not tight with floor or ceiling	Demountable partition wall, tight with floor & ceiling	Gyp on wood stud, tight w/ floor & ceiling	Gyp on metal stud,tight w/ floor & ceiling	Gyp on insulated stud, tight w/floor & thru ceiling	Fixed, tight with floor and slab above
Size/density of open workstations Gross sqft/wkst ______	< or = to 36 sqft workstation size	<48 sqft	<64 sqft	<80 sqft	<100sqft	<150sqft	>150 sqft
Distributed Noise: % of workstations <20 ft.from open meeting, coffee, copy, main circulation...	>40% of worksta. W/in 20ft.	20-40% of worksta	10-20% of worksta	2-10% of worksta			<2% of worksta
HVAC noise	Low frequency rumble	Noticeable hiss/ squeak/clang/tone	cycling	Even/quiet sound			
Masking Sound Y/N?	Too loud >50dB(A)/	Too quiet <30dB(A)	Noticeably unbalanced				
Office Protocols?	Identify those in practice: no using speaker phones, quiet phone ringers, no using headphones, use of headphones, no conversations adjacent to individual workstation, no interruptions if ______________, other: ____________________						

Figure A1. Acoustic TABS worksheet.

Appendix B

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.

Figure A2. Workstation data sheet.

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